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THE REACTION PRINCIPLE IN PETROGENESIS

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INTRODUCTION

It is now many years since petrologists first began to think of the crystallization of a molten magma in terms of the physico-chemical principles governing the behavior of solutions. In the study of ordinary solutions a condition frequently found was that known as the eutectic relation. In the simple case of two components, each lowered the melting-point of the other to the temperature of the eutectic point, at which temperature both solids separated side by side from a solution of fixed composition, the eutectic mixture. This case and the analogous condition in systems of more components are now so familiar to petrologists that they need not here be enlarged upon. The concept of the eutectic was early seized upon by petrologists and has been one of great utility in petrogenic theory. It accounted for the low melting temperatures of mixtures of minerals that are individually highly refractory. It threw light on some of the factors governing the separation of minerals from their mutual solution. But most of all, it stimulated the tendency to think of magmas in the light of the laws of solutions, or, better, of phase equilibrium, and encouraged experimental research whose expected result was the location of the composition of the eutectics for chosen mineral

mixtures. In investigation of this kind, both on its theoretical and experimental sides, Vogt took a leading part and the importance of his pioneer work cannot be overestimated.

As might have been anticipated, it was soon found that the eutectic relation did not always obtain, for, after all, it is but one of many possible relations between two or more components in any system. Very early it was realized that the existence of solid solution between two components might eliminate the eutectic relation between them. Later, as more accurate methods of experimentation were introduced, examples of incongruent melting were found, which again lead to the elimination of the eutectic. Indeed, it seems that relations between the components such that the eutectic disappears are so common in mineral systems that it may be doubted whether considerations based upon the doctrine of eutexia can longer be regarded as of any great service to petrogenic theory, in spite of their great suggestive utility in the past.

It should be realized that these non-eutectic relations should not be termed anomalies nor even apparent anomalies. They are just as definitely the result of the laws of solution as are eutectics.

This paper has been written with the object of readjusting the emphasis in our conception of mineral relations. It will be pointed out that another relation between the phases, here called the reaction relation, is very common in silicates, and is at the same time a very much broader concept, with which to approach the study of petrogenesis, than the simple doctrine of eutexia, so that it might well be set up as a principle to serve as a guide and stimulus to the search for facts.

OF CONTINUOUS REACTION SERIES

The reaction relation in a common form is illustrated by the case of the plagioclase feldspars. The equilibrium diagram of the plagioclases (Fig. 1) is of a simple and familiar type.[1] Those features of it that require emphasis in the present connection may be brought out very briefly. The crystallization of any random liquid, say Ab_1An_1, takes place in the following manner. At 1450° crystals of the composition Ab_1An_4 begin to separate. As the

[1] N. L. Bowen, *American Journal of Science*, Vol. XXXV (1913), p. 583.

temperature falls the amount of crystalline matter increases and at the same time changes in composition along the solidus curve. Thus at 1370° the crystals have the composition Ab_1An_2. In other words, the first-formed crystals have suffered a change of composition; indeed, they are continually modified in composition by *reaction* with the liquid. Crystals and liquid mutually influence each other throughout the course of crystallization.

All of this is now an old story and is repeated here merely to emphasize the marked difference in crystallization between a mixture in such a system and one in a eutectic system. In this latter, a crystal once separated is no longer concerned in the equilibrium, which makes it in every respect a special case whose occurrence might be expected to be comparatively infrequent, particularly in more complicated solutions (magmas).

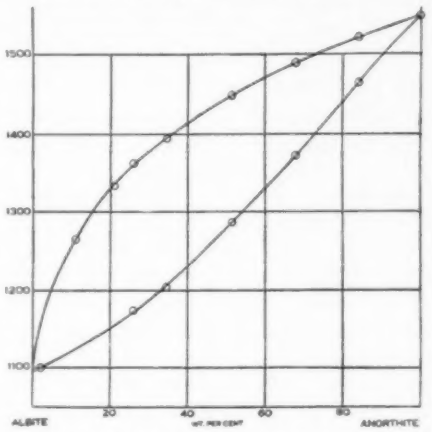


FIG. 1.—Equilibrium diagram of the plagioclase feldspars.

On account of the continual reaction relation between crystals and liquid in a solid solution series such as the plagioclases, it is proposed, for the purposes of the present paper, to call such solid solutions a *continuous reaction series*. The term will apply to any solid solution series, whether to a complete series such as the plagioclases or to each separate series in the case of incomplete solid solution.

The essential feature of a reaction series, the reaction relation of crystals and liquid, is retained when the series becomes a part of a more complex system. This is true even when the end members of the series bear a eutectic relation to the newly added component, as is well shown when diopside is added to plagioclase. The

equilibrium diagram of this system is given in Figure 2. Again it is a familiar diagram that has been fully discussed in other places,[1] but certain features of it require emphasis in the present connection.

A mixture of composition F (diopside 50 per cent, Ab_1An_1 50 per cent) begins to crystallize at 1275° with separation of diopside. As the temperature falls the crystals merely increase in amount.

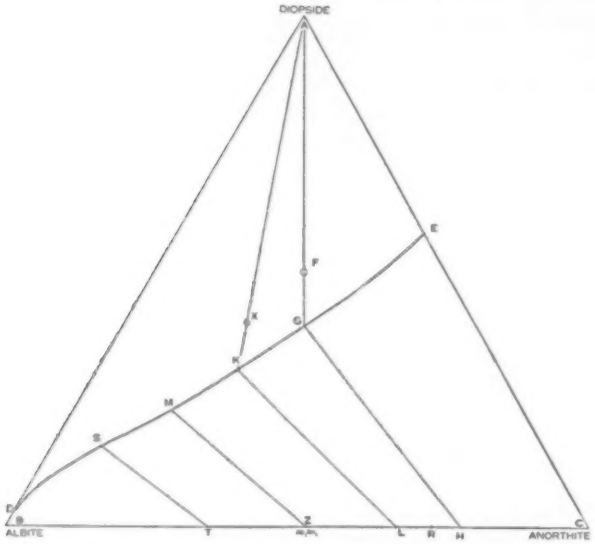


FIG. 2.—Crystallization diagram in the system, diopside-anorthite-albite

At 1235°, when the liquid has the composition G, plagioclase of composition Ab_1An_4 begins to separate and thereafter the change of composition of the liquid is represented by the boundary curve *ED*. And as crystallization proceeds along the boundary, the same reaction relation exists between the plagioclase crystals and the liquid as in the binary system. Vogt would call the curve *ED* a eutectic boundary curve or eutectic line and, to be sure, it has some properties in common with such a line.[2] It marks the composition of

[1] N. L. Bowen, *op. cit.*, Vol. XL (1915), p. 175.

[2] J. H. L. Vogt, *Journal of Geology*, Vol. XXIX (1921), p. 429.

the liquids that are in equilibrium with two solid phases. Moreover, it lies along a valley in the fusion surface and when the object is to emphasize these features no serious objection can be raised to the term used by Vogt. On the other hand, such a usage would tend toward a non-recognition of the importance of the reaction relation between plagioclase crystals and the liquids lying along the boundary curve and, in the writer's opinion, petrology will better be served by emphasizing this relation—calling the curve, say, a reaction curve. But quite apart from the question of nomenclature, the distinction is really one of fundamental importance in petrogenesis. In the case of a true eutectic line in a ternary system, the two kinds of crystals separating bear what may be called a mere subtraction relation to the liquid and once subtracted they are no longer concerned in the equilibrium. Moreover, the true eutectic line ends in a ternary eutectic point which represents the composition that all liquids of the system must finally attain and beyond which they never pass. No such rigidity obtains in a system where the reaction relation enters. The composition of the final liquid depends upon the freedom with which reaction between crystals and liquid may take place. If the reaction is complete in the example taken, the crystals are continually made over and the last of the liquid is used up by the reaction at 1200°, when the composition of the liquid is M and all the crystals have the composition Z. But if for any reason early crystals do not participate to the full in the reaction—and this may occur when zoning of crystals or sinking of crystals supervenes—the composition of the liquid may then pass beyond M and the final liquid have a composition represented by some point between M and D, with corresponding effect on the composition of the final crystals.[1]

This flexibility in the behavior of the liquid is entirely the result of the reaction relation between liquid and crystals. The course of crystallization is rendered responsive to the conditions under which crystallization takes place, for removal of crystals by zoning, sinking, or otherwise is entirely dependent on these conditions. No such response is possible in a eutectic system, for,

[1] A similar effect may of course be brought about in the binary system of the plagioclases, but it was considered unnecessary to discuss it for each case separately.

whatever the conditions, the eutectic is the goal of all liquids; all attain it; none pass it; it is a "fen of stagnant waters."

OF THE REACTION PAIR AND DISCONTINUOUS REACTION SERIES

The kind of reaction relation introduced by the existence of a solid solution series is not the only kind that is of importance in crystallizing magmas. Another type of crystallization phenomenon, ordinarily to be thought of as quite distinct from solid solution, has, nevertheless, consequences of a similar nature. This type is illustrated in several systems that have been investigated experimentally, but for our present purpose we shall discuss only cases showing phases closely related to rock minerals.

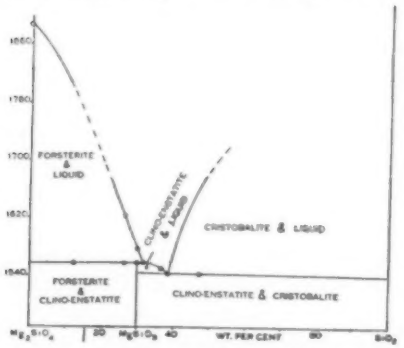


FIG. 3.—Equilibrium diagram of the system, forsterite-silica.

The equilibrium diagram of the system MgO-SiO_2 is shown in Figure 3. A liquid of composition 42 per cent MgO, 58 per cent SiO_2 begins to crystallize with separation of olivine Mg_2SiO_4 and this continues until 1557° when the olivine reacts with the liquid to form the pyroxene clinoenstatite. If the opportunity for reaction[1] is perfect the liquid is completely used up by the reaction and the mass consists entirely of olivine and pyroxene. If, on the contrary, liquid and olivine are not free to continue in intimate contact for any reason, then upon completion of all reaction possible under the circumstances, some liquid will be left over. This will proceed to crystallize in the

[1] The phrase, opportunity for reaction, is used throughout this paper without explanation. It is considered that the various factors involved have been sufficiently discussed elsewhere. The removal of crystals from a part of the liquid by their sinking is a factor limiting the opportunity for reaction as far as that part of the liquid is concerned. And so it is with the formation of a reaction armor about crystals or the squeezing out of liquid from a crystal mesh. Usually the rate of cooling is the fundamental control over these factors and therefore over the opportunity for reaction.

ordinary way giving a mixture of the pyroxene $MgSiO_3$ and silica. We thus obtain a mass consisting of olivine, pyroxene, and silica.

Again it is found that the existence of the reaction relation introduces a flexibility such that different products are obtained with varying opportunity for reaction. Under certain conditions no free silica is formed; under others a little may be formed; and under still others a considerable amount may appear. The compound Mg_2SiO_4 and $MgSiO_3$ may be called a *reaction pair*. By this is meant that crystals of the first compound react with the liquid to produce the second during the normal course of crystallization.

A reaction relation of this latter type may exist between three or more compounds and the compounds, arranged in proper order, may then be said to constitute a *discontinuous reaction series*. An example of this kind of series is given by the system H_2O-K_2SiO_3-SiO_2 as worked out by Morey and Fenner.[1] The equilibrium diagram is given in Figure 4. A liquid of composition A begins to crystallize with separation of K_2SiO_3. This is joined later by $K_2Si_2O_5$ and the two crystallize side by side, the liquid changing in composition along the boundary curve between their fields. At Q_1 the liquid reacts with K_2SiO_3 converting it into $K_2SiO_3 \cdot \frac{1}{2} H_2O$ and if the opportunity for reaction is perfect the whole mass solidifies. On the other hand, if the opportunity for reaction is limited, some liquid Q_1 is left in excess and it proceeds to crystallize along Q_1-Q_2 with separation of $K_2Si_2O_5$ and $K_2SiO_3 \cdot \frac{1}{2} H_2O$. At Q_2 the crystals of $K_2Si_2O_5$ react with the liquid to produce $K_2Si_2O_5 \cdot H_2O$ and solidification is complete if there is complete freedom of reaction. Here again there may be some liquid (Q_2) left over if reaction is for any reason limited and it will proceed to crystallize along Q_2-Q_3 with separation of $K_2Si_2O_5 \cdot H_2O$ and $K_2SiO_3 \cdot \frac{1}{2}H_2O$. At Q_3 the crystals of $K_2SiO_3 \cdot \frac{1}{2}H_2O$ are converted into $K_2SiO_3 \cdot H_2O$. In this case there is always some liquid in excess of that required for the reaction even with perfect opportunity for reaction, but there is more of it when the reaction is limited. The liquid then crystallizes along the boundary between the fields of $K_2SiO_3 \cdot HO_2$ and $K_2Si_2O_5 \cdot H_2O$, with separation of those compounds, until the isotherm of 200° is reached, and if there is no

[1] *Journal American Chemical Society*, Vol. XXXIX (1917), pp. 1173–1229.

further cooling some solution is left that does not crystallize at all.

It is plain from the outline of crystallization given that we have a reaction pair, $K_2Si_2O_5$ and $K_2Si_2O_5 \cdot H_2O$ and also a discontinuous reaction series, K_2SiO_3-$K_2SiO_3 \cdot \frac{1}{2}H_2O$-$K_2SiO_3 \cdot H_2O$. Each member of the series is produced from the preceding member by reaction with the liquid. The series is distinct from a continuous reaction

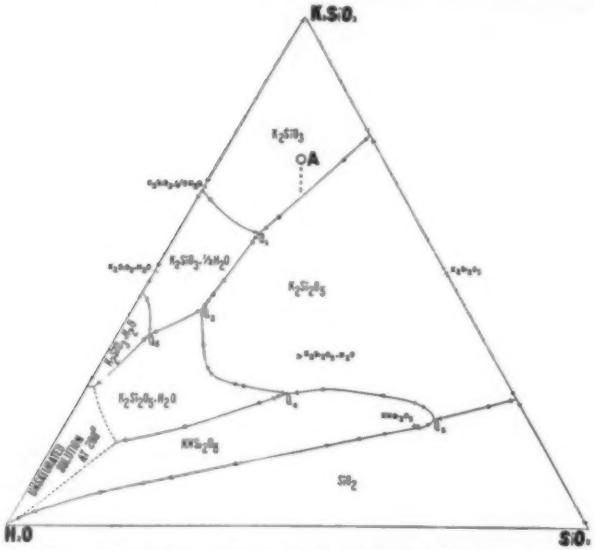


FIG. 4.—Equilibrium diagram of the system, H_2O-K_2SiO_3-SiO_2

series in that changes of composition are discontinuous, taking place in steps and not by insensible gradations as in the continuous series.

The consequences of the existence of this reaction series have been pointed out in the foregoing. Under certain conditions of crystallization we may get simply the three phases K_2SiO_3, $K_2Si_2O_5$, and $K_2SiO_3 \cdot \frac{1}{2}H_2O$. Under other conditions we may get a part or all of a long chain of products including the foregoing three and in addition $K_2Si_2O_5 \cdot H_2O$ and $K_2SiO_3 \cdot H_2O$. Moreover, when crystallization runs far down in the series we may obtain a water-rich

liquid that fails to crystallize at all. The formation of this liquid under such conditions is important in connection with the abundance of analogous liquid in certain types of magma, say, the granitic.

RELEASED MINERALS

A feature of reaction series that is important in its consequences is the fact that a compound, which otherwise would not be formed from a given liquid at all, may, as a result of failure of complete reaction, be stored up in the liquid and appear as a mineral at some later stage. Such a mineral may be regarded as *released* because of the existence of the reaction relation and it is at the same time complementary in composition to the mineral disappearing during reaction. Thus in the case of the reaction pair Mg_2SiO_4-$MgSiO_3$ free silica is released as a result of failure of complete reaction and it is complementary to Mg_2SiO_4.

THE EFFECT OF THE REACTION SERIES ON THE ORDER OF SEPARATION

We have now examined several examples of the manner in which reaction series may render the course of crystallization responsive to external conditions. In another important particular the existence of the reaction series, continuous and discontinuous, causes the process of crystallization to depart from that obtaining in the eutectic system. In the crystallization of the plagioclase feldspars a plagioclase always separates before any other plagioclase that is less calcic. There is no such thing as the separation of calcic plagioclase first from mixtures rich in calcic plagioclase and of sodic plagioclase first (followed by calcic plagioclase) from mixtures rich in sodic plagioclase, as there would be in the eutectic system. And so with the reaction pair and the discontinuous reaction series the higher member of the series always separates before the lower, if at all. We do not have a condition in mixtures of forsterite and clinoenstatite such that forsterite separates first from mixtures rich in forsterite and clinoenstatite first in mixtures rich in clinoenstatite as there would be in eutectic mixtures. On the contrary, forsterite, however small in amount, always separates first.

Thus the existence of reaction series tends to introduce a fixity in the order of crystallization, calcic plagioclase before sodic plagioclase, if at all; forsterite (olivine) before clinoenstatite (pyroxene), if at all; K_2SiO_3 before $K_2SiO_3 \cdot \frac{1}{2}H_2O$ before $K_2SiO_3 \cdot H_2O$.

SERIES WITHIN SERIES

Both the continuous and discontinuous types of reaction series may be much more complicated than the simple examples chosen for illustration. The continuous reaction series may embrace more than two components, and the reaction between liquid and crystals will then be concerned with the adjustment of the relative concentrations of all of the components. Likewise the discontinuous reaction series may consist of any number of members. More than this, any member of a discontinuous reaction series may itself be a continuous reaction series. This case is exemplified by the system diopside-forsterite-silica.[1] Here we have the discontinuous reaction series olivine-clinopyroxene-silica in which the member clinopyroxene is itself a continuous reaction series, that is, a solid solution series. The crystallization of a liquid of this system will illustrate the complexity to which the reaction relation may lead even in this comparatively simple system. The liquid D (Fig. 5) begins to crystallize with separation of the olivine, forsterite. At K the olivine crystals begin to react with the liquid to form clinopyroxene of the composition L, and as the temperature falls the liquid reacts, not only with the remaining olivine crystals to make them into pyroxene, but also with the pyroxene crystals already present to make them more calcic. Thus at F the olivine has been completely changed to pyroxene all of which now has the composition R. In this case, too, lack of opportunity for complete reaction will have an important effect upon the course of the liquid and the kind of crystals produced from it. Failure of reaction will enrich the liquid not only in silica but also in the more calcic pyroxenes.

CRYSTALLIZATION SERIES IN ROCKS

A sufficient number of examples of the reaction relation have been given to illustrate the more important aspects of it. More-

[1] N. L. Bowen, *Amer Jour. Sci.*, Vol. XXXVIII (1914), p. 207.

over the examples have in most cases dealt with members of common rock-forming groups and the prevalence of reaction series of one kind or the other among the rock-forming silicates is indicated by these few examples. The data are not at hand—and are not likely to be for some time—for a quantitative discussion of reaction

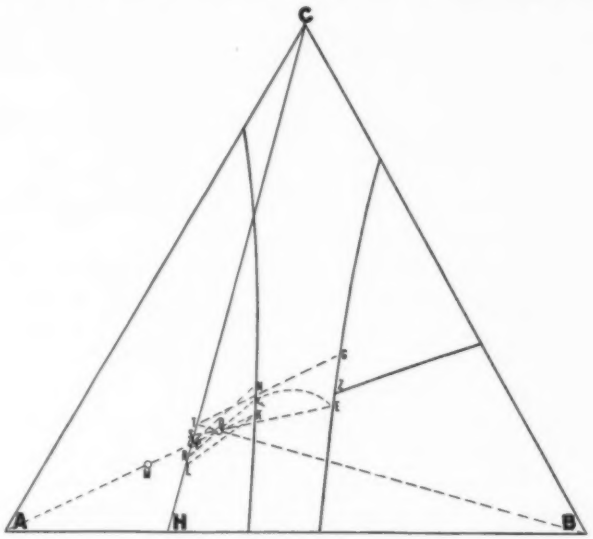


FIG. 5.—Crystallization diagram of the system, diopside-forsterite-silica. *A*, forsterite; *B*, silica; *C*, diopside; *H*, clinoenstatite, and *H–C*, clinopyroxene series.

series in mixtures corresponding to natural magmas. Nevertheless it is believed that much is to be gained from a qualitative consideration of this feature of rock-minerals.

It should be frankly stated that the existence of the reaction relation between two phases in a simple system is no guarantee of the persistence of an identical relation between them in a more complex system. In the case of the phases olivine and magnesian pyroxene, for which such a relation exists in the binary system MgO-SiO_2, it is not unreasonable to expect that the relation might be modified in more complex systems. Actually, however, it is found that the relation persists in all the more complex systems

examined, which fact renders it more likely, but by no means certain, that the reaction relation obtains in magmatic systems.[1] The service rendered by experimental investigation, so long as it is confined to a limited number of components, must lie in its indicating where a reaction relation is to be expected. We are, moreover, instructed as to what we may expect in the way of indications of reaction and thus enabled to extend our inferences to phases not formed under laboratory conditions. This brings us to the question of the criteria of the reaction relation.

A criterion of the reaction series, common to both the continuous and discontinuous type, and serving to show their fundamental likeness, is simply the tendency of one mineral to grow around another as nucleus. In the case of the continuous series this is commonly known as zoning of mix-crystals and in the discontinuous series as the formation of reaction rims, coronas, etc. Thus we have plain evidence of this kind, from a wide range of rocks, that that the plagioclases constitute a continuous reaction series and that pyroxene, amphibole, and mica form a discontinuous series. The development of these special structures is, however, dependent on particular conditions of consolidation and the lack of such structure in an individual case should not be regarded as indicating a lack of the reaction relation in that case. It must be, in part, from a general survey of mineral relations in igneous rocks that the reaction series are deduced.

Fortunately the continuous reaction series are easily picked out, for the mere existence of solid solution or variability of composition in a crystal phase is sufficient to establish that phase as a continuous reaction series. Their number is legion, all the important igneous rock minerals with the single exception of quartz being members of solid solution series. The detection of the discontinuous reaction series is not always so easy, and the element of judgment enters to some extent.

As an example of the information to be obtained on this point from a general survey of an igneous sequence let us reproduce a

[1] Vogt believes there is no reaction relation but a eutectic relation at higher pressures between olivine and pyroxene. *Jour. Geol.*, Vol. XXIX (1921), p. 528.

table given by Harker showing the mineral relations in the sequence at Garabal Hill.[1]

TABLE I

MINERAL AND ROCK SEQUENCE AT GARABAL HILL (AFTER HARKER)

	1. Iron Ore	2. Olivine	3. Augite (diallage)	4. Brown Hornblende	5. Green Hornblende	6. Biotite	7. Plagioclase	8 Orthoclase	9. Quartz
A. Olivine-diallage-rock	+	+	+	+	−	−	−	−	−
B. Biotite-diorite	+	−	−	−	+	+	+	−	−
C. Hornblende-biotite-granite	+	−	−	−	+	+	+	+	+
D. Porphyritic biotite-granite	+	−	−	−	−	+	+	+	+
E. Eurite vein	+	−	−	−	−	−	+	+	+

It will be noted that the minerals *appear* in a certain order, as they might in a system where simple eutectic relations prevailed, but they also *disappear* in a similar order, a feature that is altogether foreign to a eutectic system. In a eutectic system no mineral ever disappears.[2] The first-formed mineral is simply joined by another, the pair by a third, and so on until all the minerals appear together in a final eutectic product. Very different from this is the condition actually found, namely, the disappearance of minerals in the order in which they appear which is of the very essence of the reaction series.

Upon examination in detail it is found that 2, 3, and 4 disappear in B, 5 disappears in D, and 6 in E. From this we conclude that these phases bear a reaction (not a mere subtraction) relation to the liquid and that, as a result of the reactions, phases appearing later are formed. We arrive at the definite conclusion that 4, 5, and 6 constitute a reaction series and at the same time note indications that they are but a part of a series containing more members.

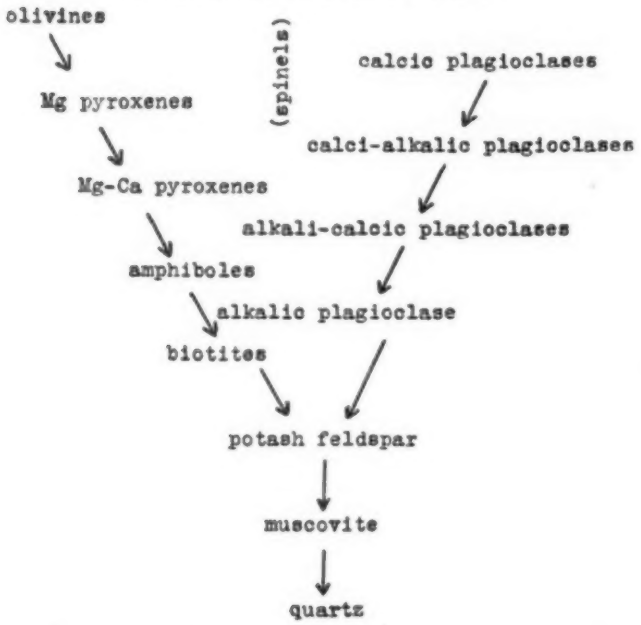
[1] *The Natural History of Igneous Rocks*, 1909, p. 131.

[2] A case of simple inversion without change of composition would require to be excluded from this statement, but it has no importance in rocks at any rate.

By piecing together the information to be obtained from the examination of such sequences and observation of the structural relations of the minerals a conclusion as to the reaction series in rocks is to be arrived at. Without going into detail as to the evidence, an attempt is made below to arrange the minerals of the ordinary subalkaline rocks as reaction series. Neither rigid accuracy nor finality is claimed. It is regarded merely as a framework upon which others may build, making such modifications and additions as may be found necessary.

TABLE II

REACTION SERIES IN SUB-ALKALINE ROCKS



Beginning at the upper end of the series in the more basic mixtures we have at first two distinct reaction series, the continuous series of the plagioclases and the discontinuous series, olivines-pyroxenes-amphiboles, etc. As we descend in these series, how-

ever, they become less distinct, in the aluminous pyroxenes and amphiboles a certain amount of interlocking begins and they finally merge into a single series.[1] This is expressed diagrammatically by a convergence of the series, with a dovetailing of the mineral names at first, and finally a joining of the two series by the arrows converging upon potash feldspar. Just where the two series merge completely is more or less a question, but it is given closely enough for our present purpose in the figure.

That the series, olivines-pyroxenes-amphiboles-biotites, constitutes a reaction series is well attested in many rock varieties. By this is meant that liquid reacts with olivines to produce pyroxenes, with pyroxenes to produce amphiboles, and with amphiboles to produce biotites. In the continually increasing water content of the series it is related to the series K_2SiO_3-$K_2SiO_3 \cdot \frac{1}{2}H_2O$-$K_2SiO_3 \cdot H_2O$. The continuous reaction series of the plagioclases is perhaps the best understood series of rock minerals. This is fortunate, for the series happens to be of particular importance in that it runs through a wide range of conditions and compositions in the rock series. We simply have a continual enrichment of the liquid in alkaline feldspar with the separation of the potash variety of alkaline feldspar as a separate phase when it has exceeded its solubility in the plagioclase mixture. With the formation of potash feldspar in the one series and of biotite in the other, the two series are now so intimately intermingled as to constitute a single series.

There is a little of the nature of eutectic crystallization in the crystallization series given in the foregoing. At early stages and as between the two series there is some suggestion of the eutectic relation in that a member of one series lowers the melting "point" of a member of the other series. Moreover the one or the other begins to separate first according to which is present in excess over certain fixed proportions. There the analogy with eutectic crystallization ends for the simple reason that there is no eutectic, no inevitable end-point where final solidification must take place when the liquid has attained a certain composition. The minerals

[1] The two series are bridged at the very outset by spinel but this has, on the whole, no great practical importance.

have a reaction relation to the liquid, not a mere subtraction relation. Each separated mineral tends always to change into a later member of the reaction series. This change of composition is effected by reaction with the liquid, and according to the opportunity for reaction the liquid is entirely used up, in some cases sooner, in others later, and only then is solidification complete.

Thus we see that rock series cannot be partitioned off into such divisions as gabbro, diorite, etc., each having a eutectic of its own. All of these belong to a single crystallization series, to a single polycomponent system, which is dominated by reaction series.

Even after what is ordinarily termed complete consolidation of the rock many changes of a reaction nature may occur between the minerals. Usually a small amount of liquid is a factor in these changes which are commonly described under the head, metamorphism. Certain aspects of these changes have been described by V. M. Goldschmidt in a paper on metasomatism.[1] It is important to note in the present connection that metasomatic reactions are not confined to the metamorphic stage but are, as we have seen, a constant feature of the whole process of crystallization of the magma. Eskola has presented evidence for believing that, at times, the original crystallization of a magma may itself take place under the conditions that are ordinarily prevalent during metamorphism. The rock then presents a "mineral facies" identical with that of a metamorphic rock of the same composition formed under the same conditions. Totally different reaction series would be concerned in the crystallization of these rocks and we have not gone far toward an understanding of these, though Eskola has done much to set us on our way.[2] The variation of conditions necessary to produce different facies is of a different order of magnitude from the variation of conditions here considered. This is largely a variation of the rate of cooling and we are here concerned mainly with the diverse rocks in the common and definitely established sequence that can be produced under the conditions of his diabase facies principally. With adequate

[1] *Economic Geology*, Vol. XVII (1922), p. 105.

[2] P. Eskola, *Norsk Geologisk Tidskrift*, Vol. VI (1920), pp. 143–94.

fractionation under conditions of slow cooling we may, however, have such concentration of mineralizers and consequent lowering of consolidation temperatures that conditions correspond to those of other facies.

EMPIRICAL RULES REGARDING ORDER OF CRYSTALLIZATION

As the result of a most extensive knowledge of the relations of minerals in rocks Rosenbusch formulated certain rules regarding the order of crystallization. When petrologists began to think of the crystallization of rocks in terms of eutectics these rules seemed to be quite at variance with theory, for this stated that those minerals should separate first that were in excess over eutectic proportions. To reconcile this with Rosenbusch's rules giving a fixed order of crystallization was a very difficult problem, and yet it was conceded that his rules represented the facts in very remarkable degree. In the light of the reaction principle no such difficulty is encountered. It is characteristic of the reaction series, as we have already seen, that however small an amount of any member may form, it always forms before a lower member of the series. In so far as reaction series control the crystallization of rocks they tend to produce a fixed order of crystallization.

Another generalization concerning the order of crystallization came from the French school of petrology. It was that the minerals separate in the order of their fusibilities, the least fusible first. This generalization, too, in the light of the doctrine of eutectics seemed to be quite absurd, but here again there is a very considerable accord with the facts. Such substances as spinel and chromite are among the most refractory materials known. Magnesian olivine has the highest melting-point of the common rock-forming silicates. The more magnesian pyroxenes stand next in the list, with the more calcic feldspars about on a par with them. The more complex pyroxenes, the amphiboles, and in particular the more alkalic feldspars are lower still. And this list corresponds very satisfactorily with the order of separation of the minerals from magmas. Again we are dealing with a tendency that is introduced by the presence of reaction series. It is a familiar character of a reaction series of the continuous type that the higher melting

members should crystallize first (witness the plagioclases), and there is a no less distinct tendency in this direction in the discontinuous reaction series.

This explanation and vindication of the doctrine of the French school is not, however, to be regarded as a proposal that we should reverse the attitude arising from eutectic considerations and accept unreservedly the statement that minerals separate in the reverse order of their fusibilities. There are too many obvious exceptions to such a rule. However, these exceptions are themselves such as might be anticipated in a system dominated by reaction series. We have seen on an earlier page that certain minerals that may be called released minerals may appear in such a system. It is apparently minerals that belong in this category that constitute the more notable exceptions. The principal of these is quartz. It is a released mineral of the reaction, olivine-pyroxene and no doubt has a similar relation in the reaction, potash feldspar-mica, a sort of hydrolysis requiring an adequate concentration of water. It is a mineral of high melting-point but separates very late—a fact that is to be connected with its character as a released mineral. In other words, it may be regarded as not actually present in the liquid at an early stage, but as released later in consequence of the reactions mentioned.

Some minerals may separate early when intrinsically present and may also appear as released minerals at later stages. Magnetite is a particularly good example. It may separate very early from a gabbro and it may be formed very late as a result of, say, the pyroxene-hornblende reaction and in particular of the mica-feldspar reaction.

PROGRESS TOWARD AN UNDERSTANDING OF REACTION SERIES IN MAGMAS

At this place it may be well to point out where we are in particular need of increased knowledge in order to understand the exact nature of the reactions occurring. It will be noted that each member of the discontinuous reaction series, olivines-pyroxenes-amphiboles-biotites, is itself a continuous reaction series. Of the olivines and the pyroxenes we know a fair amount, but practically

nothing is known as to the details of the amphiboles or the biotites as reaction series, and this means not merely their possible range of composition but also how those compositions are arranged in the series. The continuous reaction series of the plagioclases occupies a more conspicuous place than the other continuous reaction series, not merely because we know more about it, but because, as already pointed out, it enters into the rock series through a much wider range of conditions. Of the plagioclases we require to know how the potash feldspar enters into their make-up and, in the present connection particularly, at what stage in its concentration the potash molecule must appear as a separate phase. We require to know, too, the exact composition of pyroxene that forms by reaction from olivine of a certain composition, the exact composition of amphibole that forms from a certain pyroxene, and so on. These are questions on which much light may be shed by systematic equilibrium studies in synthetic minerals and by careful separation and analysis of associated minerals in various rock types. Studies of this kind are now being carried on at this Laboratory by Aurousseau on olivines, by Washington and Merwin on pyroxenes, and by Buddington on melilites. Eskola points out the importance of such work on the natural minerals, referring to it under the special name, facies petrology.[1] The results of these and kindred investigations may be profitably regarded in the light of their bearing on the reaction principle, for in their manifold details they are likely to prove excessively wearisome unless considered in relation to some such co-ordinating principle.

REACTION SERIES AND MAGMATIC DIFFERENTIATION

As the information gained from such studies of reaction series accumulates, our knowledge of igneous rock differentiation should increase conspicuously, for the reaction principle is the very life-principle of differentiation. We have seen, in our examination of the simple systems used to illustrate reaction series, how the existence of the reaction relation lends a flexibility to the behavior of a cooling liquid, renders it capable of giving different products

[1] P. Eskola, "The Eclogites of Norway," *Videnskapsselskapets Skrifter I. Math. Naturv.*, Klasse No. 8 (1921), p. 6.

according to the conditions under which it cools. This is equally true of the complex reaction series that dominate the crystallization of magmas an outline of which, for the subalkaline magmas, is suggested in Table II. As a result of the existence of the reaction relations there indicated, it may come about that a magma precipitating olivine may, at a later stage, react with the olivine and convert it into pyroxene, and, according to the extent to which controlling conditions facilitate the reaction, the whole future course of the magma is modified. If conditions are particularly favorable the reaction may be complete and the olivine may disappear, its place being taken by pyroxene. The liquid then cools further with deposition of later members of the crystal series. If conditions are not so favorable some olivine may be left unchanged and, in consequence, a somewhat different liquid is left to pass on down the crystal sequence. So it is with the reaction, pyroxene-amphibole. Not only that, but within each mineral group the reactions may be variously facilitated under different conditions. This is true not only of the members of the olivine-pyroxene-amphibole series but also of the plagioclase series, and the liquid may be entirely used up by reaction, sometimes earlier, sometimes later. It need not be surprising, therefore, that the differentiates derived from a gabbro magma may vary both in scope and quality. We may have only gabbro and diorite in one case, but a longer sequence including granite in another. We may have a potassic granite in one case and a sodic granite in another. Rapid crystallization at an early stage, with subsequent slowing-up, seems to bind up much of the potash feldspar in the early formed plagioclase and give a sodic granite. On the other hand slow cooling throughout seems to avoid this factor and give potash granites. Too little is known as yet of the details of the various reaction series to make possible any very definite statements on these points.

In offering an outline of crystallization series in rocks (and therefore of differentiation) the list has been carried only as far as the constituents of granite. This should not be interpreted as indicating that there is anything final about the granite with respect to differentiation series. We have seen in the system K_2SiO_3-SiO_2-H_2O that when any mass is cooled to 200° and no farther there will commonly be a liquid left over that never crystallizes.

The composition of this liquid lies at some point on the 200° isotherm. If the cooling were continued to 100° and no farther there would again be liquid left whose composition would be represented by a point on the 100° isotherm, and this liquid would never crystallize. And so it would be for any temperature except some negative temperature at which the water itself would appear as ice.

A similar condition will prevail in the aqueous system represented by magmas. The cooling of rocks is always limited by the temperature of their surroundings. There is always a liquid left that does not crystallize and it is probable that to the very last the rock constituents bear a reaction relation to this liquid.

In this connection the behavior of liquids crystallizing along the boundary Q_5-H_2O (Fig. 4) may be instructive. At the higher temperatures crystallization consists of the simple separation of both $KHSi_2O_5$ and quartz, but at lower temperatures $KHSi_2O_5$ separates and quartz redissolves, or, better, the liquid reacts with quartz, converting it into $KHSi_2O_5$. If the reaction is not free to take place the liquid leaves the boundary curve, passes into the $KHSi_2O_5$ field, and thereafter only $KHSi_2O_5$ separates from it, no quartz. Thus we have a reaction relation between liquid and crystals at the very latest stages and, in consequence of it, alternative behavior of the liquid.

There are some indications that in granitic liquid at the pegmatite stage, more or less similar conditions prevail. Quartz may react with liquid to produce feldspar and sometimes the graphic structure may be a result of this reaction (replacement). Why replacement should produce graphic structure in some instances and not in others is not apparent, but the possibility should be considered that graphic structure may often be the result of replacement both in rock minerals and in ore minerals. The graphic intergrowth of spinel and pyroxene seen in certain rocks can scarcely be interpreted otherwise than as due to reaction.[1] Experimental work on systems involving these phases shows pretty definitely that anything suggesting a eutectic relation between spinel and pyroxene is not to be entertained.[2]

[1] W. N. Benson, *Jour. Proc. Roy. Soc. N. S. Wales*, Vol. XLIV (1910), p. 521.

[2] Rankin and Merwin, "The Ternary System MgO-Al_2O_3-SiO_2," *Amer. Jour. Sci.*, Vol. XLV (1918), pp. 301–25; also Olaf Andersen, "The System: Anorthite-Forsterite-Silica," *Amer. Jour. Sci.*, Vol. XXXIX (1915), p. 437.

If a reaction of the kind suggested (involving quartz, feldspar, and mica molecules) is a definite feature of pegmatitic granite it is possible that failure of reaction may produce a liquid deficient in silica, just as such a liquid is produced in the system above. From this liquid feldspathoid may be deposited instead of some of the feldspar. Thus it is possible that alkalic rocks may, in some cases, be formed as a result of the reaction relation among the minerals noted. Foye has noted a very intimate relation between the granite pegmatites and nephelite syenite of Haliburton, Ontario.[1]

NOTE.—Since the foregoing was written it has been demonstrated by Morey and Bowen that leucite and orthoclase constitute a reaction pair with quartz as a released mineral. The importance of the reaction principle in connection with the origin of some alkaline rocks is confirmed by these facts but the full significance cannot be discussed here.

SUMMARY

Petrogenic theory has passed beyond the stage where the conception of eutectics can longer be regarded as of any considerable service. Experimental investigations and the study of the rocks themselves, in the light of such investigations have made it clear that the eutectic relation is unimportant but that another relation between liquid and crystal phases, here called the reaction relation, is of fundamental significance. The ordinary solid solution series such as the plagioclases may be regarded as a *continuous reaction series* because during crystallization each member is produced from an earlier member by reaction with the liquid, the variation of composition being continuous. There are also *discontinuous reaction series* exhibiting related characters but with discontinuous changes of composition. The series olivine-pyroxene-amphibole-mica is a prominent example among the rock-forming minerals.

On the basis of these considerations the minerals making up the rocks of an igneous sequence can be arranged as reaction series and it is the existence of such series that controls the crystallization and differentiation of the rocks of the sequence. Even the graphic structure, usually regarded as a eutectic structure, is probably to be considered the result of reaction between the phases in many examples.

January, 1922

[1] *Amer. Jour. Sci.*, Vol. XL (1915), p. 436.

AN OUTLINE OF THE PHYSIOGRAPHIC HISTORY OF NORTHEASTERN ONTARIO[1]

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The region here referred to as northeastern Ontario is one about 250 miles square, lying between Lake Superior and the Quebec boundary and reaching from Lake Huron north to the Transcontinental Railway. Its topography has been described so many times in reports of the Geological Survey and of the Ontario Bureau of Mines that no extended account of it is needed in this place. The region is referred to by geologists and topographers as a glaciated peneplain. As a matter of fact it is a hilly country and only conveys an impression of flatness when a large area is seen at one time. Viewed from the top of one of the more commanding hills the horizon appears as an even line and the intervening hills can be seen to stand at about the same elevation. The rivers have slopes of only 5 to 10 feet a mile, and the highest and lowest points on the railways which cross the region are 1,350 and 600 feet above sea.

This condition holds true for most of northeastern Ontario. There are a few places, however, where the relief is greater, and where significant traces remain of a former topography of more rugged character. There is, for example, one hilltop, about 40 miles west of Sudbury, from which one can see, on a fine day, a line of white hills on the southern horizon that certainly remind one of mountains. These are the Lacloche Mountains, to which further reference will be made. It also requires considerable scientific faith to acknowledge the wild country bordering Lake Superior as plainlike or nearly plainlike.

In the case of a true plain, like the Mississippi basin, or the western plains of Canada, the impression of tranquillity conveyed by the landscape is borne out by the rocky structure underneath.

[1] Read before Section E, American Association for the Advancement of Science, December 27, 1921.

The rock formations are all sediments, deposited by the subdued agencies of water or of wind. They lie in horizontal beds, free from stress.

The mild topographic aspect of most of northern Ontario might lead one to expect somewhat the same undisturbed condition underground. This is not found, however. It is not asserted here that some of the rock formations are not flat-lying or nearly so. Some of them are; but the prevailing condition is quite different. Characteristically, the stratified formations of northern Ontario are folded, twisted, sheared, and broken in the most extraordinary manner. They spring from deep underground in arches that are abruptly truncated by the surface of the peneplain. In places they have been broken by faults so great that the two sundered parts of a formation, that once lay face to face, are now found from a few hundred feet to a mile apart. They are cut by dikes and sills of rocks that were once molten, and a large share of the present surface of the region is now underlain by batholithic masses of granite, once molten, a hundred miles or so in diameter, and of unknown depth. The condition is one of suspended geological turmoil of incredible magnitude and violence.

There is something dramatic and stirring to the imagination in this contrast between the mild landscape of the present northern Ontario and the evidence of telluric convulsion that lies just beneath it; a contrast which impels one to speculate about the cause of this violence, in what manner it expressed itself at the surface of the earth, and what have been the processes of change between then and now.

The characteristic geological features of this region, as contrasted with those of a true plain, are the extreme deformation of the stratified formations, and the presence of igneous formations, particularly the batholiths of granitic rocks. If one studies a geological map of North America (Fig. 1), it is soon apparent that, outside of the great Precambrian Shield region, to which northern Ontario belongs, the greatly folded and faulted rocks are confined to the mountain regions—the Western Cordillera and the Appalachian Mountains along the Atlantic Coast. It can be seen at the same time that great granite masses, the batholiths, are present

in these mountain regions, and nowhere else in the continent, except, of course, in the Precambrian Shield.

This conjunction of batholithic intrusions with mountain systems is no new observation. It has been long noted and there

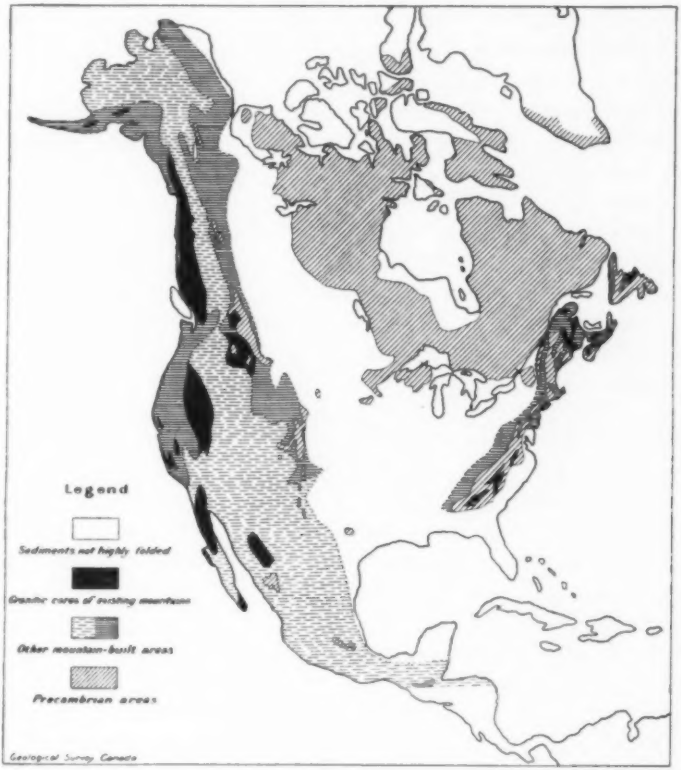

FIG. 1.—Map of North America to show the distribution of batholithic intrusions in relation to mountain-building.

has been much speculation as to the nature of the association—whether the compression and upheaval of the earth's crust caused the igneous invasions or whether the latter were causes or mere concomitants of mountain-building. Nor has the analogy between

the deformed strata and intrusive batholiths in mountain regions and in the flat, Precambrian Shield, been overlooked; but the apparent total absence of actual mountains in the Precambrian Shield, as well as its enormous area, exceeding that of any known mountain system, have led geologists to accept the theory of Precambrian mountain-building with reservations, or even to prefer the explanation that the Precambrian Shield is part of the original crust of a once molten world.

Let us compare the mountains of North America in respect to their ages, their topographic aspects and the abundance in them of batholithic rocks. The accompanying illustration (Fig. 2), compiled by J. F. Wright, of the Geological Survey, Ottawa, shows a series of representative cross-sections through the Rocky Mountains, the Coast Mountains, the Appalachians, the stumps of the ancient Acadian Mountains of Nova Scotia, and through a part of the peneplain of northeastern Ontario. The sections are arranged in order of age from youngest to oldest, are all referred to sea-level and drawn to the same horizontal and vertical scales, the relief being exaggerated twenty-one times.

The Rocky Mountains, which date from early Tertiary time, reach elevations of 10,000 to 12,000 feet, have an extremely sharp profile and reveal no batholithic intrusions, although some distance south of the line of section the Ice River syenite mass does reach the surface. The Coast mountains, of Jurassic age, reach about 7,000 feet above sea, and more than one-third of the section is of batholithic granitic rocks. These mountains are scarcely less sharp in profile than the Rockies; but that is due to the fact that they have been elevated twice and are now being carved a second time. The Appalachians were formed about Permian time, and have suffered erosion for a correspondingly longer time than the Coast and Rocky mountains. They reach only 2,800 feet above sea, have a comparatively gentle skyline, and erosion has laid bare a larger proportion of their granite core. The Acadian Mountains can be called such only in a genetic sense. They possess a relief of only a few hundred feet, and their granite core is freely exposed. They are the barely recognizable roots of mountains, and not more deserving of the designation than those shown in the next and last section.

Reference was made in the first paragraphs of this paper to Lacloche Mountains, south of Sudbury, as one of the topographic

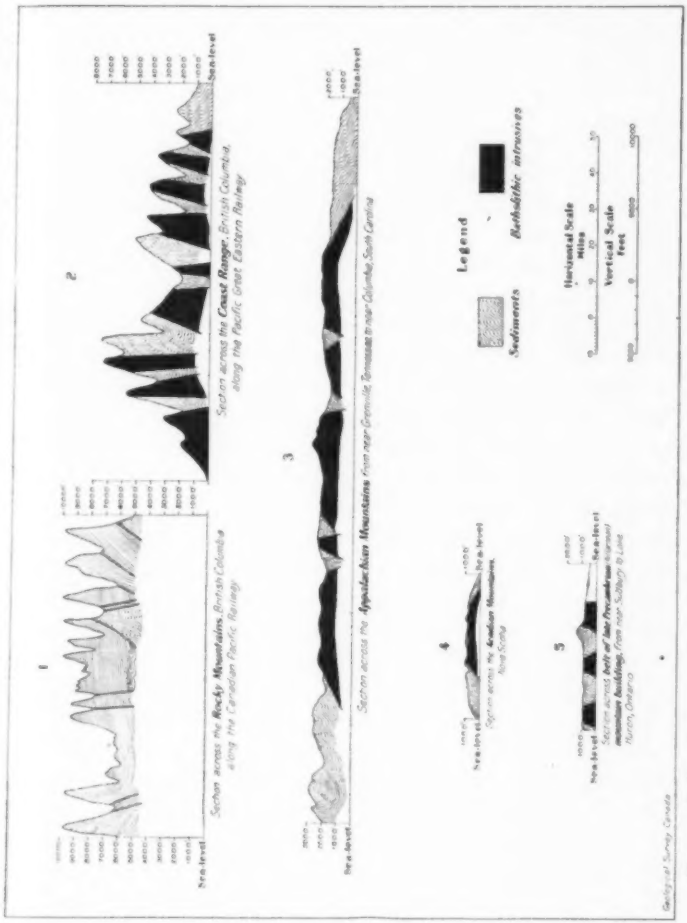

FIG. 2.—Series of cross sections of the mountain chains of North America to show the progressive effect of erosion in laying bare batholithic intrusions, and to show also the genetic relationship between mountain-building and the geology of the Precambrian field.

features that can scarcely be included as part of the Precambrian Shield peneplain. They rise in a solid, broad-based range 60 miles long and as much as 800 feet above the surrounding country.

Their mountainous aspect is enhanced by the fact that they consist of white, Lorrain quartzite and, when seen from any considerable distance, look as if they were covered with snow. The last of the five cross-sections in Figure 2 is through Lacloche Mountains. The sediments forming these mountains are Precambrian (Huronian), and the intrusive granitic batholiths are late Precambrian (Killarney).

Figure 2 has been introduced for the purpose of demonstrating that the associated phenomena of regionally deformed strata and batholithic intrusion are results and criteria of mountain-building and that by sufficiently protracted erosion a mountain system may be reduced to a peneplain having the topographic appearance and geological characteristics of northern Ontario. Endeavor will now be made to apply these criteria to the Precambrian Shield and to outline the chief events in the physiographic history of the northeastern part of Ontario, proceeding from the present as far back in time as the geological record has been interpreted.

Figure 3 shows the distribution of the essential geological elements in northeastern Ontario with which this thesis is immediately concerned. It also contains a tabular record of the geological periods. Periods not represented by rock formations in the region are shown in brackets. The larger spaces represent gaps in the record of intervals of erosion, and an attempt has been made to indicate, conservatively, by the size of the space, the length of time unrepresented by rock formations.

Let us take that part of the record from the Ordovician period to the present. Only a few of the series of formations are present—the Ordovician, Silurian, part of the Devonian, a little of what Mr. Keele regards as Cretaceous,[1] and the Pleistocene. All these formations lie horizontally or dip at very low angles. The Ordovician, Silurian, and Devonian are limestones, shales, and sandstones that contain fossil remains of marine animals. The Cretaceous contains beds of lignite and was presumably laid down on land or very near land. The Pleistocene consists of glacial bowlder clay and stratified clays and sands laid down in postglacial lakes. The careful studies of glacialists, Coleman, Johnston, Taylor, and others, have

[1] *Summary Report, Geol. Surv., Can.* (1919), Part G.

FIG. 3.—Map of Northeastern Ontario to show the known distribution of the batholithic intrusives (Painters) which are of three distinct ages and are related to three corresponding processes of mountain-building.

shown that the northeastern part of the continent, released from its load of ice, has readjusted itself, since the Glacial period, by gentle rising and tilting movements. There are no violently disturbed formations among these. There can be no doubt, then, that from Ordovician time until now northeastern Ontario has experienced only gentle oscillations in level and shallow marine submergence.

Let us take next the section of time from the beginning of the Bruce period until the end of the Keweenawan. This time is represented by a blanket of sediments aggregating over 30,000 feet in thickness, in the southern part of the region of northeastern Ontario, but thinned out to nothing by erosion, toward the north. The Bruce series is in part a land formation, and was for the remaining part apparently laid down at the edge of a continent; the Cobalt and Keweenawan series are both continental. In the northern part, these formations (represented by the Cobalt series) lie almost flat, or in open folds. Consequently it can be said with assurance that from the time of their deposition this northern part of the region has experienced no movements but those of rise and fall and mild compressional folding. Tracing these sediments southward, however, they become progressively more closely folded. South of a line drawn eastward and westward through Wanapitei Lake, the folds are tight and have a definite eastwest, axial course. Small masses of granite, intrusive in all these formations, appear at Cartier, at Sudbury, and at other points and, finally, in a line running northeasterly from Killarney, the Bruce series and later Precambrian sediments are abruptly truncated by a granite batholith of undetermined extent. How far southward this condition extends cannot be ascertained, because, from Lake Huron southward, the Precambrian formations are covered by the horizontal Palaeozoics.

It is abundantly clear that—if the associated phenomena of close regional folding and batholithic invasion indicate mountain-building—in late Precambrian time the southern part of the region shown on this map was compressed to form a system of mountains. These mountains occupied only the southern part of northeastern Ontario. They extended west along the south side of Lake Superior

at least as far as Duluth. How far eastward they extended is not known, nor, owing to the cover of Palaeozoic sediments, how far south.

Between Keweenawan and Ordovician time these late Precambrian (Killarnean) mountains were worn down to a condition probably not greatly different from that of the Adirondacks today, and certainly greater relief than the Lacloche Mountains of today, for these latter have since endured additional erosion from Palaeozoic time onward. A few peaks of the Killarnean Mountains now project through the Palaeozoics on Manitoulin Island; and bore-holes that have been made near by in the search for oil indicate a submountainous local relief of more than 800 feet in the floor upon which the Ordovician formations were laid.

Let us next consider the period of time that elapsed from the commencement of deposition of the Doré sedimentary series until the Timiskaming series and Sudbury series were completed. The Doré series is almost certainly of continental origin. It is thought to have been deposited under conditions like those which governed the deposition of the silts and gravels in the interior plateau of British Columbia. The Keewatin volcanics are believed by some geologists to be of submarine origin, owing to the abundance among them of ellipsoical greenstone; but the writer can find no evidence to support this view. It appears, rather, that they were deposited on land and in small bodies of water. Recent studies of the Timiskaming series by Mr. H. C. Cooke[1] indicate a continental origin for this series also. Judging by the extremely variable thickness of the sediments throughout this group, their coarse texture, and apparently local deposition, the region may have been one of considerable topographic relief during the entire time.

Except in the southern portion of northeastern Ontario, these formations are extraordinarily folded, schistified and faulted, and invaded by granite batholiths of huge size. In fact, they are represented now only by irregular patches which were down-folded low enough to escape erosion. If intense regional disturbance and batholithic invasion indicate mountain-building, it must be con-

[1] "Kenogami Lake and Larder Lake Areas," *Geol. Surv., Can.*, Memoir in course of publication.

cluded that following Timiskaming time the whole region, shown in Figure 3, was mountain-built. The southern portion was long afterward involved in the Killarnean mountain-building and, in that part, any evidence of this earlier orogeny was pretty completely demolished; but there is little doubt that the older mountains extended over the whole region.

Between the finish of Timiskaming sedimentation and the commencement of the Bruce period these older, pre-Huronian mountains must have been uplifted, carved, and completely destroyed, for the Bruce series lies upon a peneplained surface evidently quite as maturely eroded as the surface of today. The evidence for this has been discussed at length in various Geological Survey reports,[1] and need not be repeated. Attention need be directed here only to the length of time required for this complete physiographic cycle; the Appalachian Mountains, which are not yet nearly so completely leveled, have existed since Permian time.

Just as the Killarnean mountain-building demolished in the southern part of the region the evidence of earlier geological history, so it might be expected the pre-Huronian mountain-building, which extended over the whole region, would have obliterated all of the geological record anterior to the deposition of the Doré series. This is not wholly the case. When the Timiskaming series was first described by W. G. Miller,[2] he noted that it contained granite pebbles. Many years before, Logan noted the presence of granite bowlders in the Doré series, though, at that early stage in Canadian geological work, he could not be sure of the position of this series in the geological scale. These granite inclusions in the oldest known sediments have afforded ground for much speculation regarding the nature of the surface from which they were derived, and upon which they were deposited.

It was not until 1920 that the ancient granite which supplied these pebbles was identified *in situ* beneath the Doré series, near Michipicoten Harbor. At that place the Doré series lies tilted at an angle of 50° or more against a basement of older rocks, from

[1] M. E. Wilson, *Geol. Surv., Can.*, Memoir No. 39; W. H. Collins, *op. cit.*, Memoir Nos. 33, 95, and another not yet published.

[2] *Ann. Rep. Ontario Bureau of Mines*, Vol. XIX, Part 2, p. 62.

which it derived most, if not all, its pebbles and bowlders. This basement is in part composed of schistose volcanics and in part of gray granite. Its extent, away from the Doré series, has not been worked out and will be very difficult to determine; but there is quite enough to indicate that a third granite, older than the Killarney and the pre-Huronian granites, exists, and had been laid bare in large volume in pre-Doréan time.[1] Was this pre-Doréan granite indicative, like its successors, of a third mountain-building activity that took place in a time too remote for the mind to comprehend?

Regarding the physiographic conditions governing the deposition of the Doré series the authors of the report mentioned speculate as follows:[2]

> The writers are inclined to visualize Michipicoten district at the commencement of Doréan time as a region of rugged relief and waning volcanic activity. During early Doréan time this land surface, devoid of vegetation, was eroded rapidly, some of the deep-seated granite masses being uncovered to provide the great quantities of granite pebbles and bowlders found in the Doré conglomerate. The rude granite and porphyry conglomerate and associated formations in the lower part of the series were formed nearly in place by rock disintegration, with a consequent aggradation, or wearing down of summits and filling in of depressions in the surface of the country.

SUMMARY OF PHYSIOGRAPHIC HISTORY

1. The Doré series, the earliest known Precambrian sediment in northeastern Ontario, was deposited as a continental formation upon a surface of rugged topography. An earlier period of mountain-building and erosion is suggested by the presence, subjacent to the Doré conglomerate, of an older granite mass, apparently of large dimensions.

2. From Doréan time until the end of Timiskaming time the region was apparently a land area of considerable, if not high relief, and the seat of prolonged volcanic activity.

3. A period of mountain-building (pre-Huronian) and complete reduction to a peneplain followed, affecting the whole region. A

[1] W. H. Collins and T. T. Quirke, *Geol. Surv., Can.*, Memoir in course of preparation.

[2] *Loc. cit.*

conception of the time involved is obtainable by comparison with the rate of formation and reduction of the Rocky, Coast, and Appalachian Mountains.

4. From the Bruce period until the Keweenawan the region was apparently a land area or one of shallow and intermittent submergence.

5. Following or during the Keweenawan another (third) process of mountain-building (Killarnean) took place which affected only the southern portion of the region. These Killarnean Mountains were reduced to a state of fairly low relief before the Ordovician marine sediments were deposited upon them.

6. From Ordovician time until the present the region has been subjected only to gentle epeirogenic oscillations and shallow submergence; its relief was low throughout this interval and it now forms a glaciated peneplain.

7. From the earliest time of which a geological record remains, the region of which northeastern Ontario is part, has behaved as a positive element of the earth's crust.

A NEW OCCURRENCE OF CRISTOBALITE IN CALIFORNIA

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Cristobalite, one of the rarer high-temperature forms of silica, was first described from the andesite of Cerro San Cristobal, near Pachuca, Mexico, by vom Rath,[1] and was established as a distinct mineral species by Mallard.[2] Artificial cristobalite has been prepared in the Geophysical Laboratory at Washington and its properties and its relation to the other forms of silica have been studied by Fenner.[3] Silica bricks are made up of artificial cristobalite and tridymite, and so these minerals are of some importance to the metallurgist.

The work of the Geophysical Laboratory is extremely valuable, but of especial interest to the mineralogist and petrographer is the actual occurrence of these minerals in nature. The laboratory production of such artificial minerals is largely to aid in the interpretation of natural occurrences. Cristobalite has been known from five or six foreign localities for some time and in 1918 the writer[4] described it from two American localities, both in California. Since that time he has obtained specimens from five additional American localities.

The cristobalite described in this paper, like the Yellowstone Park occurrence recently described,[5] is found in a rhyolitic obsidian. The exact locality of the specimens could not be ascertained. The material was placed in the writer's hands by Mr. R. M. Wilke, mineral dealer of Palo Alto, California. Mr. Wilke obtained the specimens from a prospector, who would not divulge the locality. Mr. Wilke, however, says "I am sure the place is somewhere in the

[1] *Neues Jahrb. Min.* (1887), pp. 1, 198.
[2] *Bull. Soc. Min. France*, Vol. XIII (1890), p. 172.
[3] *Amer. Jour. Sci.* (4), Vol. XXXVI (1913), pp. 331–84.
[4] *Ibid.*, XLV, pp. 222–26.
[5] *Amer. Mineralogist*, Vol. VI (1921), pp. 4–6.

Science & Industry
Department

northwest corner of San Bernardino County, to the northwest of Barstow, probably within 40 to 50 miles from Barstow." The geological map of California compiled by Professor James Perrin Smith and published by the California State Mining Bureau shows a number of outcrops of volcanic rocks northwest of Barstow, and so Mr. Wilke is probably correct as to the approximate locality.

THE OBSIDIAN AND ITS LITHOPHYSAE

The specimens consist of dark gray to almost black obsidian ($n = 1.483 \pm .003$) with a faint banded structure and bright vitreous luster. In thin fragments the obsidian shows on microscopic examination numerous, minute, rod-shaped crystallites arranged in parallel lines and a few microlites.

The obsidian contains many light gray spherulites which range from 5 to 25 mm. in diameter and are fairly evenly distributed, though sometimes two of them coalesce. The spherulites are more or less flattened; some of them are elongate, and most of them are somewhat irregular in outline. With a few exceptions they are hollow and hence may be called lithophysae. It is estimated that the spherulitic material occupies only about a fifth to a half of the original space. The spherulites are for the most part ruptured, and deep cracks extend almost to their margin, so that the spaces left are usually very irregular in outline. The cracks give some of the lithophysae a superficial resemblance to mud-cracks. The thickness of the spherulitic material is often only about a tenth of the radius of the original cavity.

Accompanying the obsidian specimens were a number of loose spherulites or lithophysae, which had been broken out of the obsidian. They are much more regular than the imbedded lithophysae just described. One of these is shown in the photographic enlargement (Fig. 1). They have a more or less well-defined hollow space at the center and show a slight tendency to concentric structure, as may be noticed in the photograph.

It seems probable that both the expansive force of the gas within the cavity and the tension due to cooling of the surrounding glass were responsible for the formation of the lithophysae.[1]

[1] For a discussion of the origin of lithophysae, see paper by Wright, *Bull. Geol. Soc. Am.*, Vol. XXVI (1915), pp. 255–86.

MINERALS OF THE SPHERULITES

The solid portions of the spherulites consist of two minerals, orthoclase and cristobalite, and of these orthoclase predominates. The orthoclase and cristobalite occur in fibrous aggregates, which on microscopic examination prove to be intergrowths. In spots, which are probably cross-sections, they have an intricate interlocking structure which suggests graphic texture. The orthoclase is

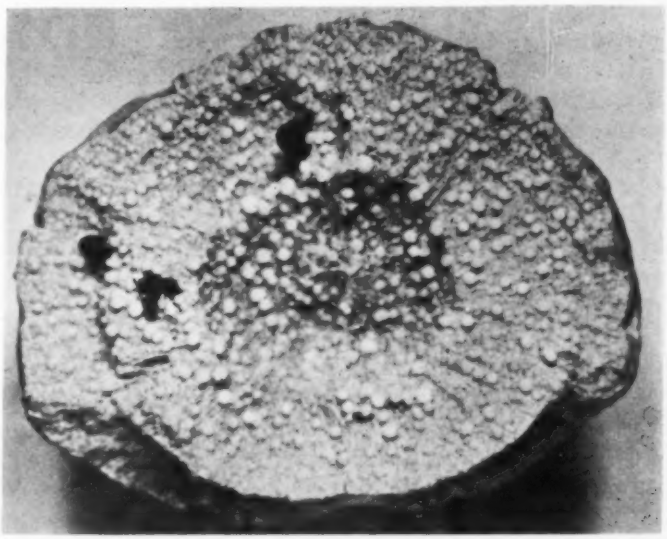


FIG. 1.—(×5) Cristobalite and Fayalite in a Lithophysa of the Obsidian from San Bernardino County, California.

cloudy, while the cristobalite is clear. The cristobalite is identified by its index of refraction, which is slightly greater than 1.480. Most of the cristobalite areas are isotropic, but occasionally they show very weak double refraction. The double refraction is uniform, which distinguishes the cristobalite from the glass which has practically the same index of refraction.

It seems probable from the descriptions in the literature that such orthoclase-cristobalite spherulites are characteristic of rhyo-

litic obsidians, but have not been recognized before on account of the difficulty of distinguishing the cristobalite. It was with great difficulty that the writer succeeded in proving that the mineral intergrown with the orthoclase was cristobalite.

Imbedded in these larger spherulites are numerous, very minute, spherical bodies, which consist largely of orthoclase with small amounts of cristobalite. These probably represent earlier formed spherulites of orthoclase which have been recrystallized during the later main period of spherulite production. Such composite spherulites have been described by Rutley[1] from another locality in California. Rutley speaks of "isotropic matter" between the rods or fibers of orthoclase, which in all probability is cristobalite.

There is a little magnetite imbedded in the spherulitic material.

MINERALS OF THE LITHOPHYSAL CAVITIES

The following minerals were identified in the lithophysae: orthoclase, cristobalite, tridymite, opal, magnetite, and fayalite. These minerals occur on the walls of the lithophysal cavities and the specimens make beautiful microscopic mounts (Fig. 1).

Orthoclase.—On the free surface of the cavities the orthoclase takes on the form of branching rods with weak birefringence and positive elongation (parallel to γ). The index of refraction is $1.517 \pm .003$.

Cristobalite.—The cristobalite occurs in minute (0.2–0.5 mm.) translucent white spherulites, which are scattered over the surface of the lithophysae as illustrated in the photograph. In fragments the cristobalite shows a well-defined spherulitic structure with elongation of the crystals parallel to the faster ray a. There is intricate polysynthetic twinning and the extinction is oblique. The double refraction is very weak.

The index of refraction of the cristobalite is $1.483 \pm .003$, which was determined by means of immersion liquids. This determination positively distinguishes it from tridymite which has indices of refraction of 1.469–1.473.

The specific gravity of the cristobalite is $2.36 \pm .04$, which was determined by means of a mixture of acetylene tetrabromid and

[1] *Quar. Jour. Geol. Soc.*, Vol. XLVI (1890), pp. 423–28.

benzol. (It sank in the liquid in which gypsum [sp. gr. = 2.32] remained suspended and floated in the liquid in which brucite [sp. gr. = 2.39] remained suspended.)

In still another respect did the mineral agree with cristobalite. It is infusible and on heating to a high temperature by means of a blowpipe it became semi-transparent and on cooling it suddenly became translucent again. This sudden change in appearance, which may serve as a blowpipe test for cristobalite, is due to the conversion of the high-temperature β-cristobalite to the low-temperature α-cristobalite, which, according to Fenner, takes place in artificial cristobalite at a temperature varying from 198 to 240° C.

Tridymite.—The exterior of most of the cristobalite spherulites when examined with a high-power binocular microscope are seen to be studded with very minute six-sided crystals of tabular habit. These are identified as tridymite by their index of refraction, $n = 1.475 \pm .005$. The tridymite is transparent in contrast to the translucent cristobalite. Some of minute cristobalite spherulites apparently are converted into tridymite, but careful microscopic examination shows that the cristobalite is simply covered with the tridymite.

Opal.—Several of the lithophysal cavities are coated with a thin layer of hyalite opal (n slightly less than 1.45), which was evidently the last mineral formed. No chalcedony or quartz could be detected in any of the specimens.

Fayalite.—A few, small (1 mm.), brown, transparent crystals of fayalite (Fe_2SiO_4) are found on the free surfaces of the lithophysae. Three crystals (dark areas) are shown in the photograph. They are tabular in habit and resemble the fayalite from the spherulitic obsidian of Yellowstone National Park. The fayalite has an index of refraction greater than 1.74 and gives an iron borax bead test. Some of the crystals have been altered to a black opaque substance.

Magnetite.—Very minute octahedral crystals of magnetite are visible with the high-power microscope.

FORMATION OF THE MINERALS

The minerals lining the walls of the lithophysae evidently were formed by hot gases liberated by the crystallization of the spheru-

lites. The orthoclase and cristobalite are largely products of recrystallization of the spherulites. The cristobalite probably was formed at a comparatively high temperature and as the temperature became lower, tridymite was formed, and at about the same time fayalite and magnetite appeared. The opal is the only mineral that was formed by ordinary solutions. The oxidation of the fayalite, a slight staining of the lithophysae, and whitening of the orthoclase rods are the result of weathering.

CRISTOBALITE IN SPHERULITIC OBSIDIAN

The Yellowstone Park occurrence, the San Bernardino County occurrence of the present paper, and two undescribed Californian occurrences, all taken together, point to the conclusion that cristobalite is one of the characteristic minerals of spherulitic obsidian. In fact it seems to be more common in such rocks than tridymite. It is probable that in some cases cristobalite has been identified incorrectly as tridymite. For example the minute pellets referred to and figured by Iddings[1] in the spherulitic obsidian of Yellowstone Park are probably cristobalite instead of tridymite.

[1] *Seventh Ann. Rept. U.S. Geol. Survey* (1888), p. 264, Pl. 12, Fig. 3.

FAULT FEATURES OF SALTON BASIN, CALIFORNIA[1]

JOHN S. BROWN
U. S. Geological Survey

OUTLINE

General Features
Surrounding Mountains
The Basin Floor
Stratigraphy
Formation of Salton Basin
The Indio Fault
Faults Southwest of Salton Basin
Valleys Formed by Faulting
Type of Faulting
Age of Faulting
References

GENERAL FEATURES

The Salton Basin is a great natural depression in the southeastern corner of California (Pl. I). Its lowest elevation is 273.5 feet below sea-level,[2] and the lowest part of the basin is now occupied by the more or less ephemeral lake known as Salton Sea, which was created in 1905 by the accidental escape of Colorado River during the diversion of irrigating water to Imperial Valley. Physiographically, Salton Basin is continuous with the depression occupied by the Gulf of California, and the only topographic barrier that prevents the access of sea-water to the basin is a delta dam built up in recent geologic time by Colorado River. At its lowest point this dam is less than 50 feet above sea-level.

SURROUNDING MOUNTAINS

The axis of the basin trends southeast-northwest, and at its northwest extremity the basin narrows nearly to a point, being connected by San Gorgonio Pass to the Pacific Slope. Mountain ranges from 2,000 to 10,000 feet in height flank the basin on the

[1] Published by permission of the Director of the United States Geologic Survey.

[2] There is some question as to whether the exact elevation of the lowest point of the basin, now covered by Salton Sea, is −273.5 or −287 feet. See *U.S. Geol. Surv. Water-Supply Paper 213*, p. 30, for discussion and statement that former figure is probably correct.

northeast and southwest, reaching their highest elevation in the vicinity of San Gorgonio Pass, where the basin is narrowest. The mountains on the southwest are generally known as the Peninsular ranges. They extend down into Mexico, and form the crest of the peninsula of Lower California. They include the San Jacinto, Santa Rosa, Vallecito, and Laguna ranges, and their crest separates the drainage of Salton Basin from that of the Pacific Slope. The summit of the Peninsular Mountains is well watered and generally timbered. Along it there are numerous tracts of gently rolling land sculptured into only a moderate relief. Such are Pinyon Flat, Montezuma Flat, and the region near Jacumba. These tracts are doubtless remnants of the surface of the region before it was uplifted to form the present mountain chain. The eastern slope of the Peninsular ranges, however, is precipitous, and its dissection deep.

The San Bernardino Mountains and other ranges form the northeast wall of the basin. To the southeast these break up into a series of low, disconnected ranges. All of them are barren rock masses, at whose feet are gathered great débris fans.

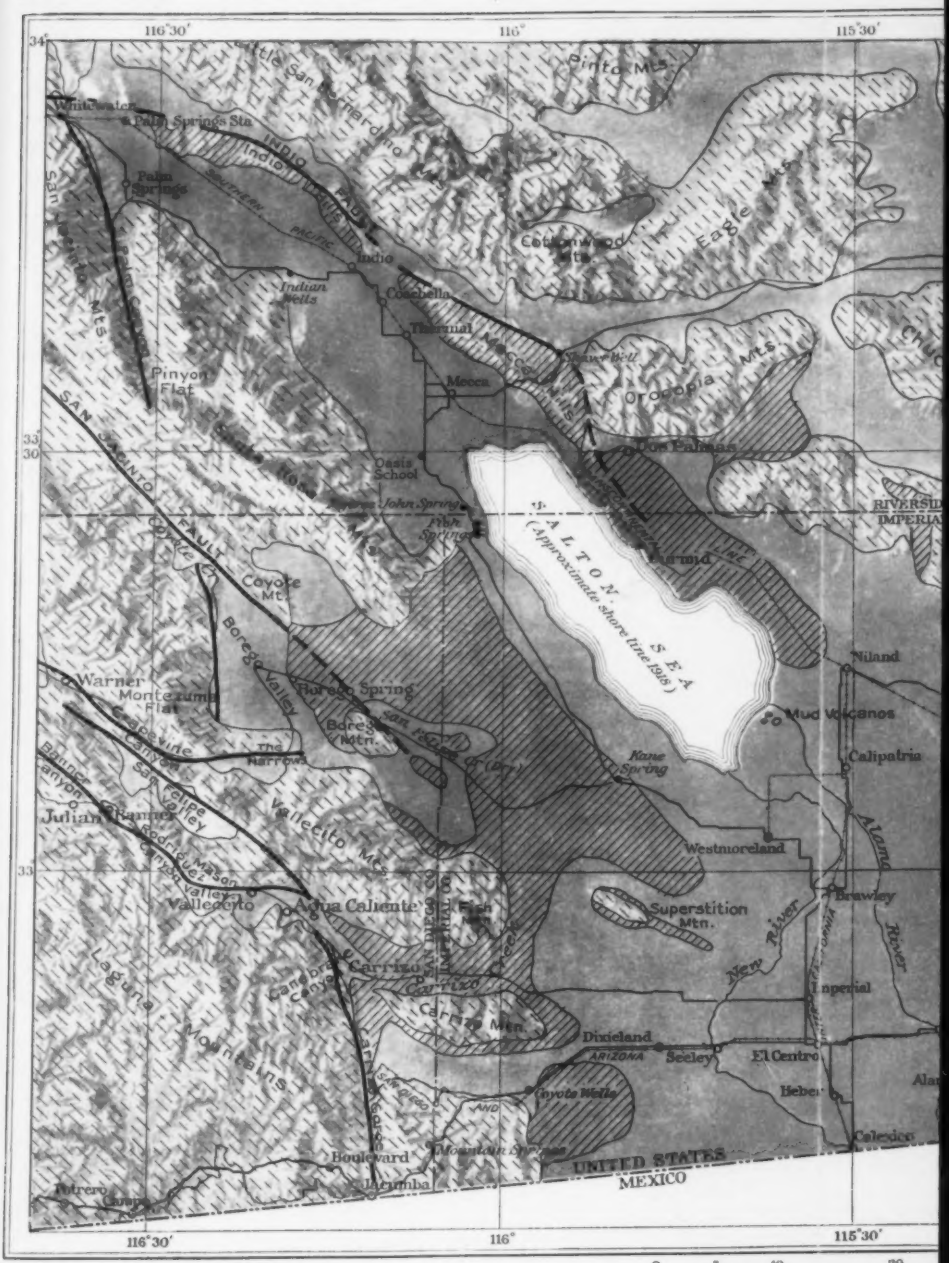
THE BASIN FLOOR

A great part of the basin floor is a monotonous plain formed of alluvium brought in from every side. In the center the alluvium is fine silt, but at the mountain borders it is a coarse fanglomerate. Over some of the basin floor there is a considerable deposit of sand in the form of dunes. About the borders there are, at various places, exposures of soft, folded, sedimentary beds, which have been carved into picturesque badlands. Since the basin is practically rainless, vegetation is scant, and restricted to desert plants, such as creosote, cacti, ironwood, and, at places, mesquite.

One other feature of the basin floor deserves mention. Near its center, at the southeast end of Salton Sea, is a large group of active mud volcanoes, associated with small exposures of recent lava (obsidian).

STRATIGRAPHY

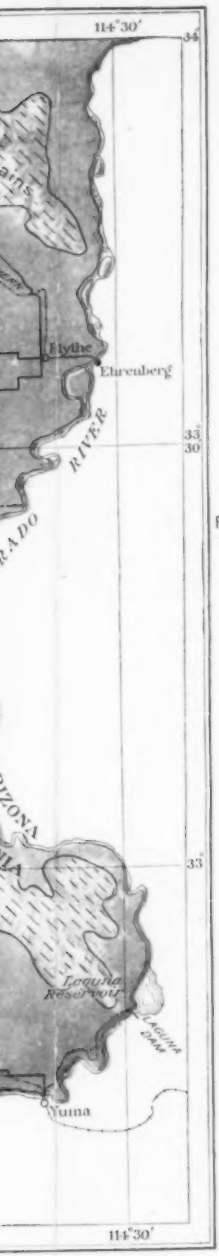
The rocks of Salton Basin have been studied in detail at only a few places. For the purposes of this paper, however, they fall naturally into three classes. The first class comprises pre-Tertiary



Reconnaissance map of the geology and topography of

topography of Salton Basin and vicinity

PLATE I



EXPLANATION

Quaternary alluvium

Late Tertiary sedimentary rocks

Pre-Tertiary Igneous and metamorphic rocks

Fault

Relief shading by J.H. Renshawe from data supplied by author

crystalline rocks, and forms the basement rock of all the region. There are large bodies of schist and gneiss, and smaller amounts of marble and quartzite. The age of these metamorphics is unknown. Most of them are Paleozoic, but a part probably is pre-Cambrian. Then there are still greater masses of granite, monzonite, and diorite intruded into the metamorphic rocks. These intrusives are probably Mesozoic. The various crystalline rocks constitute the mass of all the mountain ranges.

The second division of rocks consists chiefly of sedimentary beds of late Tertiary age. The series has a total thickness of several thousand feet, and consists of sand, shale, and conglomerate, with some salt and gypsum. Generally the beds are more or less folded and broken, but they are everywhere soft and poorly consolidated. On them is developed the badland topography mentioned above. In the Carrizo Creek region these beds contain an abundant late Tertiary marine fauna. Elsewhere they are apparently unfossiliferous, and probably terrestrial in origin.

Interbedded with the Tertiary sediments at some places are beds of basaltic lava and tuff sometimes 100 to 200 feet in thickness. These volcanics constitute only a small portion of the series.

Quaternary alluvium is the last division of the rock section. It forms most of the basin floor, and fills many of the adjacent valleys. Its areal extent is greatest of the three classes.

FORMATION OF SALTON BASIN

Salton Basin has evidently existed as a marked depression since times previous to the latter part of the Tertiary period, for it has received sediment during the formation of the last two rock series. Neither the Quaternary nor the Tertiary sediments are displaced by any such vertical movements as must have occurred during the formation of the basin. The Tertiary beds are seldom found at elevations above 1,000 feet, and the Quaternary shows but few recognizable displacements and these are of small size.

It has been tacitly assumed by geologists that the basin originated as a dropped fault block, or graben. This hypothesis, suggested by the topographic features, is greatly strengthened by the fact that the basin lies directly on the course of the San Andreas

Science & Industry
Department

rift, a notable fault along which occurred the displacement that caused the San Francisco earthquake of 1906. The California Earthquake Commission traced this fault continuously from San Francisco southeastward to the very tip of Salton Basin. In its report[1] the commission suggests that the rift probably continues southeast, and is connected in some way with the formation of the basin. In the Peninsular Mountains, southwest of the basin, there are also several well-recognized faults, portions of which have been mapped, but these have generally not been traced eastward to their visible terminations. These faults and their relation to the faults described here are shown in Figure 1.

The evidence of faulting in this region is as a rule, derived from the topography, and can only rarely be established by stratigraphic criteria. Igneous and metamorphic rocks, such as compose the mass of the mountain ranges, are so homogeneous in nature that it is often impossible to determine differences in the rocks exposed on either side of a fault, while the Quaternary material which fills most of the valleys has been deposited since the faulting occurred and obscures it in many places.

THE INDIO FAULT

At the base of the crystalline ranges (Little San Bernardino, Orocopia, etc.) bordering the upper part of the northeast side of the basin, lies a conspicuous chain of low, badland hills in which are exposed the late Tertiary sedimentary beds, and occasionally small patches of the underlying bedrock. This chain of hills is separated by a slight break into two ranges known as the Indio Hills and Mecca Hills. The Indio Hills have a total length of 20 miles, and a width of 2 or 3 miles. The Mecca Hills are also about 20 miles long, and at some places are 4 or 5 miles wide. The general slope of the hills is southwest, where they dip beneath the basin floor. They are separated from the crystalline ranges northeast by a trough from 1 to 3 miles in width filled with coarse alluvial débris. At some places the canyons that head in the main mountains cut entirely across the hills, as at Shaver Canyon and the Thousand

[1] *California Earthquake Commission Report*, Carnegie Inst. of Wash., 1910.

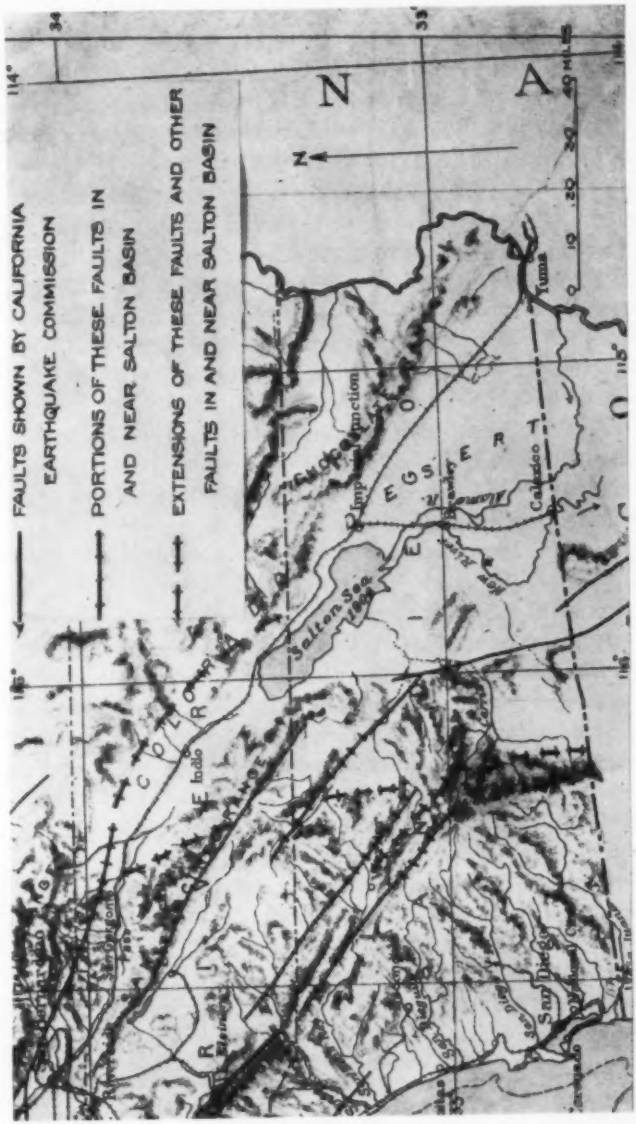


FIG. 1.—Prominent faults of Southern California. (After California Earthquake Commission)

Science & Industry
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Palms. At other places they are deflected by the foothills into long, longitudinal valleys between the crystalline and Tertiary rocks.

The Indio and Mecca Hills have undoubtedly been lifted from the basin floor by a fault for which the name of Indio fault is suggested. This fault passes along the northeast border of the hills formed by the Tertiary rocks. Near Indio there is for several miles a steep and very perfect scarp, generally not more than 100 to 300 feet in height. The broken Tertiary beds dip southwest from the present face of this escarpment at angles of about 45°. Along the northeast side of the Mecca Hills the scarp is less perfect, but still constitutes a very well-defined ridge. West of Dos Palmas it is a low bluff along the east base of a point of clay hills.

Although the Indio fault as here described was observed only at a few scattered points, it appears reasonably certain that it extends throughout the length of the Indio and Mecca hills. The most critical point at which it should be examined is the contact with the crystalline bedrock in the Orocopia Mountains, where there appears to be no marked separation of the crystalline range from the bordering sedimentary foothills. The fault doubtless continues at least as far south as an isolated hill of Tertiary material near Durmid, which has probably been elevated in the same manner as the hills farther north. Its total length, then, is about 50 miles, and its form an arc of gentle curvature. Its northwestern end has a trend nearly west, and lies in the direct line of probable extension of the San Andreas rift, from which the actual separation is only a few miles in length. The conclusion seems justified that the Indio fault represents the extension of the San Andreas rift. At the southeastern end the fault-trend is more nearly south, and points suggestively toward the mud volcanoes.

It should be noted that the throw of this fault is opposite to that of the San Andreas rift farther northwest, and also to the original displacement which must have formed the Salton Basin. Such reversals of throw along prominent fault lines are, however, neither impossible nor uncommon,[1] and occur at several places along the course of San Andreas rift farther northwest.

[1] The Bright-Angel fault in the Grand Canyon is a case in point. *Science*, April 24, 1908, p. 667.

FAULTS SOUTHWEST OF SALTON BASIN

The faulting along the southwestern side of the basin is apparently of two ages, and took place in somewhat different directions, the intersection of the two fault systems probably accounting for the present irregular outline of the basin. Thus great mountain salients, such as the Santa Rosa Mountains, the Vallecito-Fish mountain spur, and the projection of the Peninsular Mountains along the Mexican Boundary, are separated by big re-entrant valleys, such as San Felipe Valley and the Carrizo Creek Valley.

The oldest of these fault systems, if this inference is correct, has a strike about N. 10 W. and is represented by three notable escarpments. One lies along the east base of the San Jacinto Mountains, passing up Palm Canyon. Another is at the west side of Borego Valley. The third extends from Agua Caliente Springs southward up Carrizo Gorge, along the east face of the Laguna Mountains.

Evidence of a fault along the northeast and east face of Mount San Jacinto was obtained near Whitewater. Just west of Whitewater Point the mountain face is composed of pink and gray granite, and of a grayish marble. The marble and granite are arranged in layers turned on edge with a strike about N. 20 W., and a dip of 75° or more to the northeast. Although the quantity of marble is much less than that of the granite it constitutes a considerable part of the mountain mass, the layers ranging from a few inches to 50 feet in thickness. The alternation of rocks is well exhibited in a prospect tunnel in Sec. 23, T. 3 S., R. 3 E., where the material penetrated has the appearance of a gigantic fault breccia, and the contact surfaces are abundantly slickensided. This intermixture of material probably resulted from step-faulting, the successive breaks along many parallel lines causing an intimate mixture of the different rocks. Associated with this prominent fault line is the warm spring at Palm Springs, whose water is believed to be derived from granitic rocks[1].

West of Borego Valley no observations were made to confirm the existence of a fault except to note that the mountain front in that region is a very steep and straight escarpment from 2,000 to 4,000 feet in height.

[1] The inference is based on unpublished analytical data.

Science & Industry
Department

The southernmost fault scarp of this series was observed in Canebrake Canyon, and at Agua Caliente Springs. At both places the mountain front for several hundred feet from the lowland border consists of rotten, grayish granite, broken into minute joint blocks, kaolinized, and altered. Farther in the interior of the mountains the rock is dense and unweathered. There is much evidence of hydrothermal alteration, a very natural thing to expect, at Agua Caliente Springs, where a large number of springs, part of which yield warm water, issue from the granitic rocks.

Cutting across this first system of faults is a system which strikes approximately N. 45 W., and which is represented by several prominent faults. The most northerly fault of this system is the San Jacinto fault, which passes south and west of San Jacinto Mountains, extending through Hemet Valley and down Coyote Canyon. For several miles it traverses the northeast side of Borego Valley.[1] The uplift along this fault was on the northeast. Coyote Mountain on the northeast of Borego Valley is part of a prominent spur elevated in this uplift, and is bordered on the southwest by well-defined scarp, which displaces Tertiary beds. It is probable that the San Jacinto fault extends at least as far as Borego Mountain, but it is much obscured in that direction by recent alluvial deposists. Movement occurred along this fault at the time of the San Jacinto earthquake of 1899.

Several faults which have been recognized in the vicinity of Warner Valley[2] extend southeastward into the western part of this region. One of these which passes nearly through Warner Hot Springs traverses Grapevine Canyon, turns nearly east along a part of San Felipe Creek, and disappears near The Narrows. Its uplift was on the northeast, and the tongue of granitic rock south of Borego Valley and in the vicinity of The Narrows is believed to have originated from the uplift. A fault extends from Warner Valley down the headwaters of San Felipe Creek, and its eroded scarp forms the northeast side of San Felipe Valley, being a promi-

[1] H. W. Fairbanks, *California Earthquake Commission Report*, Carnegie Inst. of Wash., 1910, p. 47.

[2] A. J. Ellis, and C. H. Lee, "Geology and Ground Waters of the Western Part of San Diego County, Cal.," *U.S. Geol. Surv. Water-Supply Paper 446*.

nent mountain wall for 12 or 15 miles. Another fault passes through Banner Canyon and Rodriguez Canyon, and extends along the north side of Mason Valley and Vallecito Valley, the mountain walls of these valleys probably representing considerably eroded fault scarps. The last two faults unite in the vicinity of Agua Caliente Springs, and are not known to continue farther, but may extend along the north side of Carrizo Valley at the base of Vallecito Mountains and Fish Mountains.

VALLEYS FORMED BY FAULTING

Associated with the second system of faults are several peculiar valleys for whose formation the faults have been responsible. The largest of these valleys are Borego Valley, San Felipe Valley, Mason Valley, and Vallecito Valley. Collins Valley, adjacent to Borego Valley, and a little valley less than a mile in extent at Banner, were formed in the same way. All of these valleys have for their northeast boundary a high, steep mountain wall which originated as a fault scarp along some one of the faults mentioned above. Thus Borego Valley and Collins Valley lie southwest of the San Jacinto fault. The general shape of each valley is triangular, and the south and west sides are much more irregular in outline than the northeast side, the mountainous borders on these sides being also somewhat less abrupt than those on the northeast. Most of the valleys are high at the southwest, and the drainage is to the northeast. This has probably been the natural result of the tilting of the faulted strips, which have all been dropped down on the northeast and elevated on the southwest.

Most of the faults have forced the drainage to follow northwest-southeast directions, particularly in the various canyons such as Coyote Canyon, Grapevine Canyon, and Banner Canyon, but some streams, such as San Felipe Creek, northeast of San Felipe Valley, and Banner Creek at Banner, occupy deep gorges which cut directly across the fault scarps at the northeast border of these valleys. It is probable that these streams existed before the faulting, and that the faulting took place gradually, the streams cutting down as fast as the rocks were lifted across their beds. A further suggestion that the earlier drainage lines may have had a northeast trend is

afforded by the granite ridges which divide some of the valleys. San Felipe Valley, for instance, is cut nearly in two by a low spur of granitic rock projecting from the southwest, while Mason Valley and Vallecito Valley are entirely separated by such a ridge, except for a very narrow, rock-cut canyon. These ridges may very likely represent drainage divides which existed before the faulting.

TYPE OF FAULTING

Most of the faulting observed is of the normal type. The Indio fault is associated with much folding, and it is possible that it may be in part due to thrust movements.

AGE OF FAULTING

The age of the various faults is very difficult to establish, since the age of the rocks displaced is so indefinitely known. The original settling of the Salton Basin must be pre-late Tertiary in age, because in the resulting basin great thicknesses of late Tertiary sediments were deposited. Considerable faulting has occurred since the deposition of these beds, such as that along the Indio fault, and the San Jacinto fault where Tertiary beds are displaced. The fact that movement has occurred along the recognized fault lines during recent notable earthquakes in California indicates that some of those faults are still active; and the excellent state of preservation of many of the scarps suggests that much of the displacement along some of them has occurred in Quaternary time.

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MARINE UPPER CRETACEOUS AND A NEW ECHINOCORYS FROM THE ALTAPLANICIE OF BOLIVIA[1]

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Johns Hopkins University, Baltimore

It is not surprising that rocks of Upper Cretaceous age should be present on the high plateau of Bolivia since the gypsiferous shallow water phase of the Upper Cretaceous which represents the several typically developed marine horizons that are so abundantly represented in the more northern parts of the Andean geosyncline (e.g., in central Peru), is conspicuous in the Eastern Andes of Bolivia and furnished the writer with marine fossils at two localities in the Department of Potosí.

It may be true also that these marginal Upper Cretaceous deposits of Bolivia, which are essentially reddish sandstones and gypsiferous shales, with subordinate beds of limestone, are present in considerable amount beneath the late Tertiary and more recent deposits that make up most of the surface of the high plateau except where older rocks are folded and project through these thick, surficial deposits.

No Cretaceous rocks have heretofore been known from the Altaplanicie, however, although it is true that Steinmann called the rocks at Corocoro Cretaceous. This was based solely on the fact that the Corocoro rocks were red, and as the red rocks near Potosí, 375 km. distant, were known to be Cretaceous, the unwarranted assumption was made that the Corocoro rocks also were Cretaceous. Many have followed Steinmann's opinion, as, for example Douglas in his recent geological sections across the Andes,[2] although it would seem that if color is to be an age criterion, an Englishman would consider red as indicative of Old Red or New Red age, as did Forbes in his classic studies of Bolivian Geology.

[1] *George Huntington Williams Memorial Publication No. 9.*

[2] J. A. Douglas, *Quart. Jour. Geol. Soc. Lond.*, Vol. LXXVII (1914), pp. 1–53; Vol. LXX (1920), pp. 1–61; Vol. LXXVII (1921), pp. 246–84.

As a matter of fact the writer showed in 1917 that the Corocoro rocks were of Pliocene age[1] and this age determination is fully and completely established by detailed field studies made by Singewald and Berry in 1919, the results of which are now awaiting publication.[2]

The presence of true Upper Cretaceous in this region rests on the species of Echinocorys or Ananychites described below (Figs. 1–3), for which I am indebted to Señor Arturo Poznansky, of La Paz. It is said to have been collected at Peñas, which is just east of the southern end of Lake Titicaca in the Department of La Paz, and 55 km. northwest of the city of that name. It was not possible for me to visit the locality, but there is no reason for doubting its correctness since the specimen was newly collected at the time of my visit to La Paz and must have come from the near vicinity of the place named.

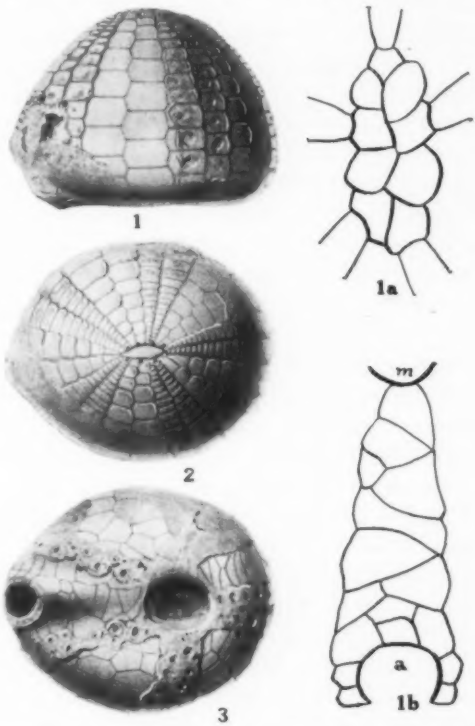
The specimen in itself is of great interest since it is, to the best of my knowledge, the first specimen of this interesting genus, so excessively abundant in the Upper Cretaceous of Europe, to be recorded from South America, and the third or fourth to be recorded from the Western Hemisphere. It does not agree with any of the numerous described species and may be called in honor of its progressive collector *Echinocorys* (*Ananychites*) *poznanskii* sp. nov.

It may be described as follows: Ambital outline elliptical, rounded in front and somewhat narrowed behind. Profile (i.e., transverse section) subcircular, the apex broadly rounded. Peristome elliptical 7 mm. in length by 10 mm. in width, situated about two-fifths back from the anterior margin, hence relatively larger and slightly more posterior in position than is commonly the case in this genus. Periproct posterior, subambital in position, large, elliptical in form, with a length of 8 mm. and a width of 6 mm. The apical system is largely obscured by calcitic incrustations. As near as it can be made out it consists of four larger genitals and five smaller oculars arranged as indicated in the accompanying sketch (Fig. 1*a*). The plastron appears to have been smooth and to comprise the sixteen plates shown in the accompanying sketch (Fig. 1*b*), and is unusual,

[1] E. W. Berry, *U.S. Nat. Mus. Proc.*, Vol. LIV (1917), pp. 103–64.

[2] Singewald and Berry, *Bull. Geol. Soc. Am.*, Vol. XXXII (1921), p. 66 (abstract).

if my interpretation is correct, in having a posterior pair of plates occluded, as indicated. Centrally the plastron becomes increasingly convex toward the periproct in which region it projects about 3 mm. below the oral plane of the test. The abulacral plates number



FIGS. 1–3.—*Echinocorys* (*Ananychites*) *poznanskii* sp. nov. 1, lateral view; 1*a*, sketch of arrangement of apical system; 1*b*, sketch of plastron, comprising sixteen plates; 2, dorsal view; 3, ventral view.

eighteen or nineteen normal pairs from the apex to the ambitus, very small at first and increasing regularly and rapidly in size downward. The pores are very much obscured by incrustation, the pore pairs being clearly seen only toward the equatorial region, where they are large and central in position, that is, some distance

within the outer margins of the ambulacrals. The inter-abulacrals are larger and there are ten normal pairs between the apex and the ambitus. Length of the type 5.1 cm.; width 4.25 cm.; height 3.95 cm.

These interesting and characteristic echinoids were figured as early as 1565 and are a striking element in the later Upper Cretaceous faunas of Europe. They appear somewhat abruptly in the Turonian, undergo but slight diversification in the Santonian, and become exceedingly abundant and diversified in the Campanian. They have dwindled to two known forms in the Maestrichtian and have a single Danian and a single Eocene survivor. They evidently found their optimum environment in the relatively clear and shallow waters in which the chalk was deposited, which may account for their singular rarity in the North American Upper Cretaceous where such a large proportion of the sediments are muddy, thus offering obstacles to both migration and colonization. In keeping with this theory there is a single small species known from the Vincentown lime sands of the Rancocas formation of New Jersey, *Ananchytes ovalis* Clark[1], and a second large species, *Ananychites texana* Cragin[2], from the Austin and Annona chalk in Texas and Arkansas. Both are exceedingly rare and, so far as I know, are represented by only the type specimens. The Rancocas formation was considered to be of Danian age by Clark[3] although it is probably Maestrichtian, and the Austin chalk should probably be correlated with the Santonian or Campanian substages of Europe. A single additional record of the genus in North America is an incidental and queried reference by Aquilera[4] to the presence of *Ananchytes sulcatus* Goldfuss in the Upper Cretaceous of Mexico.

Lambert's excellent monograph[5] of the genus renders comparisons easy and this new Bolivian species is seen to somewhat resemble

[1] W. B. Clark, *U.S. Geol. Survey Bull. 97* (1893), p. 74, Pl. XXXVI, Fig. 1 *a–h*.

[2] F. W. Cragin, *Fourth Ann. Rept. Geol. Surv. Texas* (1893), p. 145, Pl. XXV, Fig. 12; Pl. XXVI, Figs. 1, 2.

[3] W. B. Clark, *Geol. Soc. Am. Bull.*, Vol. VIII (1897), pp. 315–58.

[4] J. G. Aquilera and E. Ordoñez, *Datos para la geologio de México* (1893), p. 27.

[5] J. Lambert, "Étude monographique sur le Genre Echinocorys," *Mem. Mus. Roy. d. Hist. Nat. Bèlge*, Tome 2 (1903).

the European Danian species, *E. sulcatus* Goldfuss, but it appears to be most similar to the European Campanian and Maestrichtian forms, *E. Cotteaui* and *E. Duponti*, described by Lambert, who prefers to use the generic term *Echinocorys* proposed in pre-Linnean time (1732) by Breynius, and re-adopted in 1778 by Leske, rather than *Ananchites* Lamarck (1801) which has been adopted in recent American texts. The age of the Bolivian deposit would appear to be Campanian, although more definite confirmation is desirable before this correlation can be accepted as final.

FORMER COURSES OF THE ANDROSCOGGIN RIVER

IRVING B. CROSBY[1]
Boston, Massachusetts

INTRODUCTION

The Androscoggin River is one of the most interesting of the many examples of disarranged drainage in New England and merits more attention than it has hitherto received.

The present study has involved a critical examination of the topographic relations of the Androscoggin and several adjacent rivers, differentiating the topography controlled by underlying bed-rock formations from the topography of surficial deposits.

Nearly all that part of the problem south and east of Berlin, New Hampshire, is covered by the topographic sheets of the United States Geological Survey; but the region north of Berlin is best shown on Hitchcock's map of New Hampshire;[2] and, finally, the hydrography of the entire area included in this investigation is shown in outline on the accompanying drainage map (Fig. 1).

TOPOGRAPHY

The drainage basin of the Androscoggin River, approximately 125 miles long in a northwest-southeast direction and 30 to 40 miles in normal breadth, may be divided into five topographic provinces, as follows: headwater, upper, middle, lower, and coastal; and in each province the river has characteristics peculiar to that province.

The Androscoggin River is formed by the junction of the Magalloway River and the drainage of the Rangeley Lakes, near Errol, New Hampshire. The headwater province extends north and east from this point to the ultimate sources of the river and will not be further considered in this paper.

[1] The writer wishes especially to express his indebtedness to President W. W. Atwood, under whose direction this work was done.

[2] C. H. Hitchcock, atlas accompanying the *Report on the Geology of New Hampshire*. New York, 1878.

The upper province includes the region between Errol and Berlin. It is bounded on the southeast by the Mahoosuc Range,[1] the

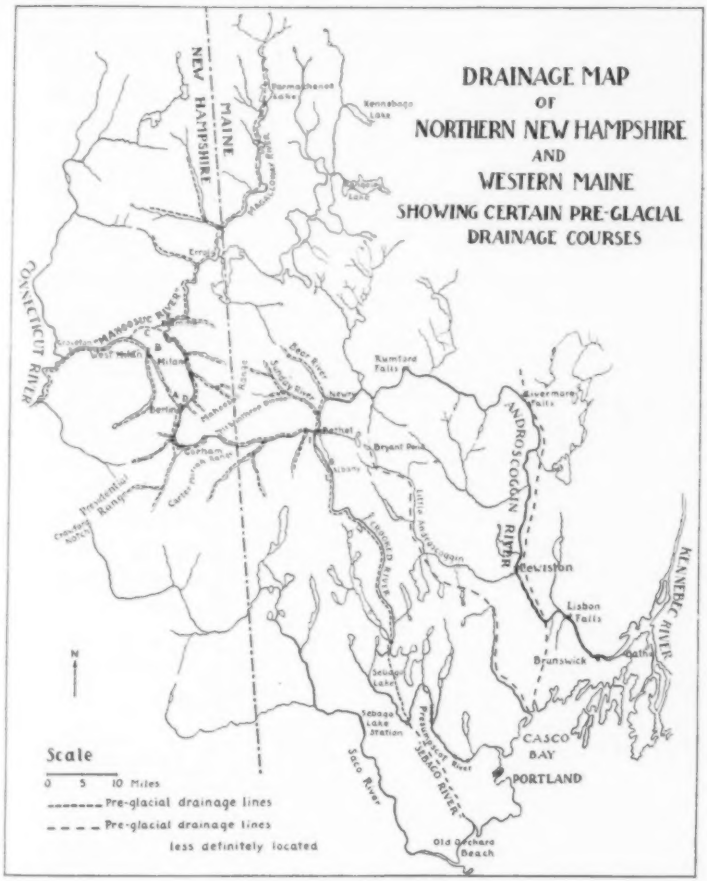


FIG. 1.—Drainage Map

northeastern extension of the White Mountains, and is characterized by broad valleys and mountains of moderate elevation. Slaty

[1] The range, extending from Gorham, New Hampshire, to Grafton Notch, Maine, and including the following mountains: Baldcap (3,100), Ingalls (3,570), Goose Eye (3,854), and Speckled (4,250), has recently been named the Mahoosuc Range.

rocks prevail in the northern part and granitic rocks in the southern part. The country is heavily mantled with glacial drift; but the existing bed-rock contours indicate that the preglacial topography was in the mature stage of dissection. The river flows southerly through this province, in a broad valley, descending 180 feet in 30 miles, or 6 feet to the mile.

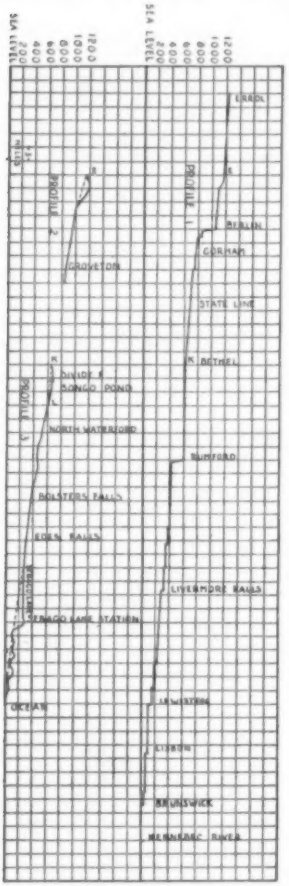


FIG. 2.—Profiles of the present and former courses of the Androscoggin Drainage

The middle province extends from Berlin, New Hampshire, on the west side of the main ranges of the White Mountains, to Bethel, Maine, on the east side, its high mountains and deep valleys contrasting strongly with the lower mountains and broad valleys of the upper province. The Androscoggin flows southerly from Berlin to Gorham through a narrow valley in granitic rocks, and then turns abruptly to the east and passes, in a deep valley, through high mountains of massive siliceous schists. These schists, the most resistant rocks of the region, form the main ranges of the White Mountains, and extend northeasterly into Maine.

In the middle province the river descends 420 feet in 30 miles or 14 feet to the mile, thus having a gradient two and one-third times as great as in the upper province. At Berlin the river drops 200 feet in several falls; and there are a number of other falls and rapids in the first ten miles below that city. Profile 1 (Fig. 2) shows the distribution of fall on the river and emphasizes the contrast of the river gradients above and below Berlin.

Comparison of the middle and upper provinces shows that in the former the valley is younger and deeper, suggesting a great change in the history of the river. These facts, together with the peculiar behavior of the river at the great bend near Gorham, where the river turns abruptly from less resistant rocks into high mountains of more resistant rocks, lead to the belief that the upper part of the valley has been occupied much longer by the river and that it formerly had another route to the sea.

The lower province, extending from Bethel to tidewater at Brunswick, is marked by broad valleys, low passes, and low, rounded mountains. As the sea is approached the mountains disappear and the hills are very low, with the exception of a few monadnocks. The preglacial topography of the region near the mountains was in late maturity and near the coast it was in old age.

In the lower province the course of the river differs greatly from its course in the other provinces in being very irregular, with many sharp turns, as can be seen on the drainage map (Fig. 1) or on the topographic sheets. In this province the river descends 635 feet in 98 miles or 6.5 feet per mile; but this descent consists of a number of falls with quiet stretches between. The numerous sharp turns, narrows and falls indicate that the present course of the river is not normal, and lead one to look for a more direct route.

The coastal province extends from the head of tidewater to the open ocean and is characterized by drowned valleys and by islands. In this province, about 8 miles below Brunswick, the Androscoggin joins the Kennebec, with a retrograde course, that is, the direction of the tributary is reversed in relation to the main stream, the apex of the acute angle between the two streams pointing up the main stream. This abnormal junction of the two rivers is good evidence that the Androscoggin is not here flowing in a normal course.

The higher ranges of the White Mountain system have a northeast-southwest trend; but seaward from these ranges the ridges have a north-south or northwest-southeast direction. This general trend of the topography seaward from the mountains is well shown by the numerous north-south elongated lakes, valleys, and ridges, and the absence of similar features with an east-west trend. There-

fore the northerly-southerly direction may be considered as normal for a valley in the region between the mountains and the sea; and the few cases of west to east courses are exceptional.

The writer believes that the present route of the Androscoggin through the mountains in the middle province is not the original course of the drainage of the watershed above Gorham, and also that the route of the river below Bethel is entirely postglacial, the present stream occupying parts of several preglacial drainage systems.

The ice sheet crossed this region in a southeasterly direction, widening the valleys and passes, and developing the characteristic U-profile.

In the mountains till is widespread, but well-defined moraines and drumlins are few. The valleys are relatively narrow, the divides are generally high, and streams are principally controlled by the bed-rock topography and not by glacial deposits.

In the lower province, just east of Bethel, the valleys are broader, the divides lower; and the streams are partly controlled by glacial deposits, while nearer the coast moraines and drumlins are common, rock hills are scarce, and stream control is largely by surficial deposits.

FORMER COURSE OF THE UPPER ANDROSCOGGIN

The present divide between the drainage to Long Island Sound and to the Gulf of Maine extends northerly from the Presidential Range between the valleys of the Connecticut and Androscoggin rivers. This divide has several low passes, one between Berlin and Groveton having a summit less than 100 feet above the Androscoggin River or 1,100 feet above sea-level. The mountains forming the divide are composed of granitic rocks and are less high and rugged than the schist mountains of the main ranges. The irregular northerly-southerly trend of the divide, and its broken character, contrast strongly with the Presidential, Carter-Moriah, and Mahoosuc ranges, which have a regular northeast-southwest trend and have only one low place, the valley of the Androscoggin at Gorham.

These facts coupled with the character of the Androscoggin valley near Gorham indicate strongly that formerly the divide was along the Carter-Moriah and Mahoosuc ranges. If this were the case, the upper Androscoggin had another outlet and the only possible alternate course would have been through the valley now occupied by the Upper Ammonoosuc to the valley of the Connecticut at Groveton.

The broad valley of the Upper Ammonoosuc extends eastward from the Connecticut and connects with the valley of the Androscoggin by three broad, low passes.

The most southerly of these passes (*A* on Fig. 3), between Berlin and West Milan, is traversed by the Grand Trunk Railway and its summit is less than 100 feet above the Androscoggin at Berlin. Dead River, a small, sluggish stream, heads in this pass and joins the Upper Ammonoosuc at West Milan. Dead River appears to have been beheaded near Berlin and before that accident it was undoubtedly large enough to make the broad valley which it now occupies.

The next pass to the north (*B* on Fig. 3) lies between West Milan and Dummer. It is broad, with a summit approximately 100 feet above the Androscoggin. No bed rock is visible in the saddle or on its slopes, and it has every appearance of being deeply drift-filled.

The third pass (*C* on Fig. 3) is about three miles farther north, where a broad branch valley connects with the Androscoggin valley by a pass approximately 100 feet above that river. This pass is very broad with gentle slopes, and no bed rock is visible.

The broad valley between Groveton and West Milan is occupied by the Upper Ammonoosuc River. The narrowest part of this valley is 6 miles west of West Milan, but it is probable that a lake a few miles to the north marks the preglacial course of the river.

The valley of the Upper Ammonoosuc was deeply filled by glacial deposits, which have been only partially cleared out by the present stream; and it is obvious that the preglacial valley was much too wide to be accounted for by the erosive action of the present river. The branch valley toward pass *C* is floored with

stratified drift. If all this drift were removed from these valleys, there would be a broad valley, ample for a large river, connecting the Androscoggin with the Connecticut.

Northeast of Berlin is a nearly level plain, rising gradually to the southeast and ending abruptly against the Mahoosuc Range.

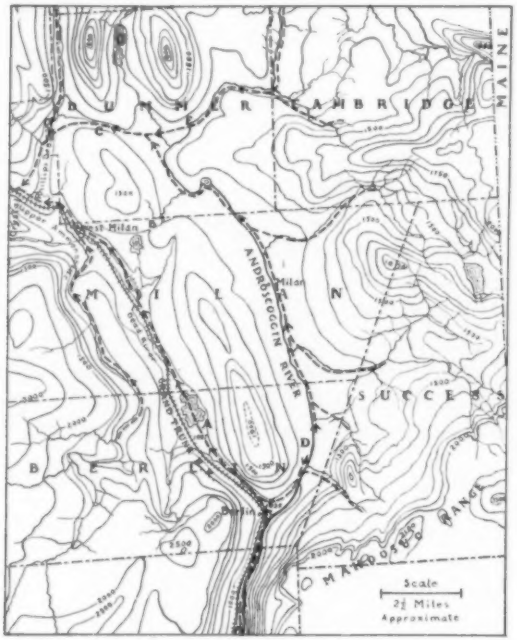


FIG. 3.—Map showing present and former drainage lines about Berlin, Dummer, and Milan, New Hampshire.

----- Former Drainage Lines

Several streams flow northwesterly across this plain and enter the Androscoggin with retrograde courses. The descent from the plain to the Androscoggin at Berlin is abrupt, indicating that the river has been rejuvenated enabling it to lower its bed faster than is possible with the smaller streams.

There are remnants of a bed-rock bench at an elevation of approximately 1,200 feet on the valley sides south of Berlin. At Gorham the elevation of the bench remnants is 1,300 feet (*1* in Fig. 4),[1] and two miles to the east their elevation is 1,400 feet (*2* in Fig. 4). The summit of Mount Winthrop (*3* in Fig. 4), a long spur projecting into the valley five miles east of Gorham, has an elevation of 1,575 feet.

FIG. 4.—View eastward from Pine Mountain, Gorham, New Hampshire

Looking eastward from Mount Winthrop, long, even-crested ridges extend into the valley; and two with elevations of about 1,100 feet appear completely to block the valley. These are evidently remnants of the floor of a valley which descended to the east from a divide where Mount Winthrop now is.

The series of bench remnants rising to the east from Berlin and culminating at Mount Winthrop mark the level of an old valley which extended from the valley now occupied by the Upper Ammonoosuc to a low pass at Mount Winthrop.

Observations from Mount Winthrop give indication of an old land surface descending on either side. On the opposite side of the present valley are benches which correspond to Mount Winthrop

[1] From a photograph by the Shorey Studio, Gorham, New Hampshire.

and represent the opposite spur of the old divide. There appears to be ample field evidence to prove that eastward from Mount Winthrop Divide the drainage was into the Gulf of Maine, and that westward it flowed to the Connecticut.

This divide prevented the Androscoggin from flowing to the east, as it now does, and the broad valley of the Upper Ammonoosuc represents its course when tributary to the Connecticut.

Of the three passes connecting the Upper Ammonoosuc and Androscoggin valleys, either *B* or *C* offers a direct route without sharp angles or reversals of direction. Pass *A* would necessitate a much longer course with a sharp turn at Berlin, and it will not be considered as the former route of the river.

A river appears, therefore, to have flowed through the present Androscoggin valley to Dummer, through pass *C* or *B*, thence down the valley now occupied by the Upper Ammonoosuc, into the Connecticut. The name "Mahoosuc River" is suggested for this stream.

Profile 2 (Fig. 2) shows the grade of this course, the full line representing the present surface and the broken line the probable bed-rock surface; and profile 1 (Fig. 2) shows the grade of the present river. A comparison of these two profiles shows that the former route has a fairly constant grade, a normal condition for a large river, while the present course drops several hundred feet in a series of falls and is characteristic of a younger river which has not yet eroded its valley to grade.

During the existence of the Mahoosuc River a stream from Mount Winthrop Divide joined a stream from Mount Washington and flowed north to the point where Berlin now stands, and then through pass A into the Mahoosuc River. Three miles north of Berlin was a low divide (*D* on Fig. 3) between the drainage to pass A and a stream which joined the Mahoosuc River at Dummer. Between divide *D* and Dummer all tributaries joined the present river with retrograde courses; and at the time when the stream in that valley flowed north instead of south, as at present, these tributaries had normal junctions with the main stream. The old drainage is shown in Figures 1 and 3.

In explanation of the existing drainage it may be stated that the modern valley of the Androscoggin below Berlin represents more erosion than could have occurred since the last ice retreat. Undoubtedly this valley was greatly widened, straightened, and deepened by the movement of ice through it, and possibly the Mount Winthrop Divide may have been removed and the present drainage brought about by ice action. But river piracy also offers a simple explanation.

The stream on the east side of Mount Winthrop Divide had a much steeper grade and thus far greater erosive power. Bethel, 17½ miles east of the divide, has an elevation of 635 feet, and the elevation of West Milan, 23 miles west of the divide, is 1,015 feet. The descent eastward from Mount Winthrop is 57 feet to the mile, while the westward descent is 24 feet to the mile. Allowance for erosion does not materially alter the relations.

From the divide to the Gulf of Maine by the preglacial course of the lower Androscoggin is 90 miles and from the divide to Long Island Sound by the Upper Ammonoosuc and Connecticut rivers is approximately 300 miles. These facts show that favorable conditions for piracy existed.

The Androscoggin River wore its valley back through the low Mount Winthrop Divide, captured the Peabody River, beheaded the Dead River at Berlin, wore through the low divide at *D*, captured several streams from the Mahoosuc Range, finally captured the Mahoosuc River, and thus started the present drainage system.

FORMER COURSE OF THE LOWER ANDROSCOGGIN RIVER

It has been pointed out that the present course of the Androscoggin, in the lower province, between Bethel and the ocean, is abnormal and is of postglacial origin.

For the preglacial course two possible routes are to be considered: eastward along the line of the Grand Trunk Railway or southward via the valley of Crooked River. The latter appears to be the more probable route on account of its lower summit and freedom from obstructions.

The Grand Trunk Railway occupies a pass in the hills near Bryant Pond with a summit elevation of 720 feet above the sea or 85 feet above the Androscoggin at Bethel. From Bryant Pond the Little Androscoggin River flows southeasterly and joins the Androscoggin at Lewiston with a retrograde course. At Snows Falls in the town of Paris the valley is blocked by a rock hill and the stream is crowded into a very narrow gorge. The height of the pass and the obstruction at Snows Falls make it appear that this is not the preglacial course of the Androscoggin. However, glacial outwash material in the valley and pass indicate that in glacial times a large stream flowed this way.

The postglacial origin of the lower part of the Little Androscoggin is shown by its retrograde course and its interruption by two falls. The preglacial course was probably through Poland into Casco Bay.

The present course of Crooked River and the basin of Sebago Lake will now be considered. Crooked River joins the Songo River a little north of Sebago Lake and the joint stream is tributary to that lake. If Crooked River is followed upstream, a surprising discovery is made: its source is only two miles from the Androscoggin near Bethel and the divide separating the two rivers is only 35 feet above the Androscoggin (Fig. 5).

The examination of Crooked River and the basin of Sebago Lake makes it appear that this route was occupied during preglacial times by a large river which flowed southerly from Bethel. This stream was formed in the vicinity of Bethel by the junction of two major streams. One of these headwater streams came from the Mount Winthrop Divide and the other from the north, probably receiving tributaries from the valleys of Sunday and Bear rivers. For convenience this preglacial stream will be referred to as the "Sebago River."

The character of the valley of Crooked River becomes of great importance when considered as a possible course of a large river. The valley is broad and has a direct course with no sharp turns. The name of the stream implies a crooked course, but the windings are all of minor magnitude; they are the meanders of a small stream flowing in a broad valley of low gradient.

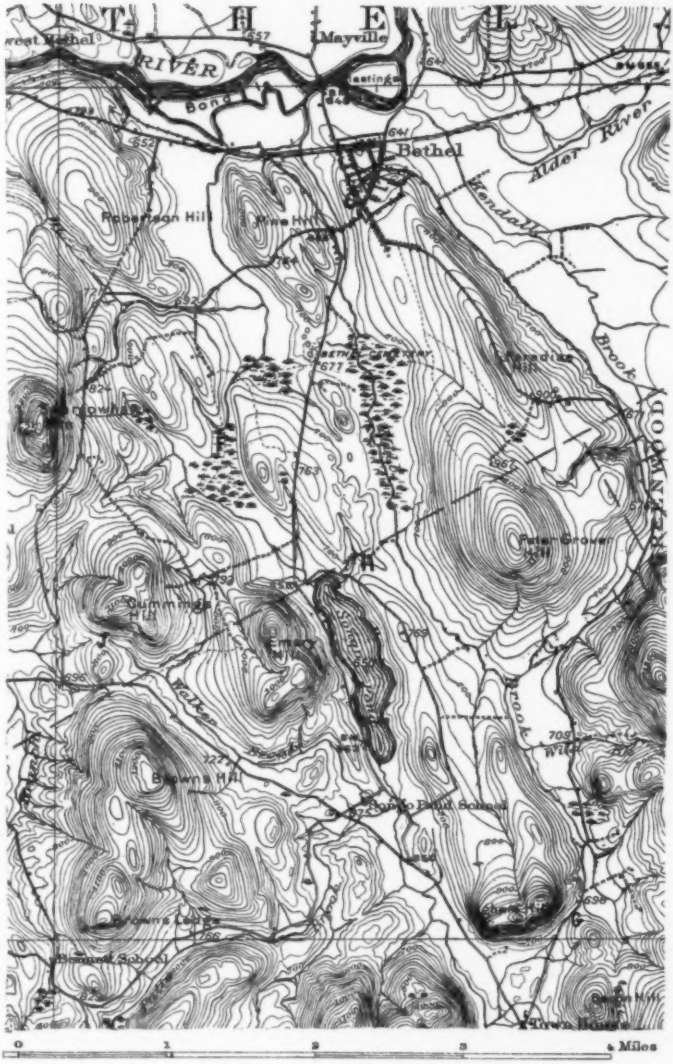


FIG. 5.—Map of the region about Bethel

On the lower course of Crooked River there are several low falls. The valley is filled with drift and in meandering across this drift plain the stream has discovered the ledges that now break its bed. The old river was probably free from falls.

At several places, in its upper part, the valley is rather narrow, but in estimating the size of valley required by the Sebago River it must be remembered that the upper Androscoggin was then tributary to the Connecticut, and the river below Bethel was smaller than the present Androscoggin. It follows that the narrow places which are in the mountains were ample for the Sebago River.

In the town of Albany, at the place marked L on Figure 1, granite bed rock outcrops in the stream at an altitude of 610 feet. The grade of the Sebago River from this point to Bethel was 3 feet per mile or the same as the present grade of the Androscoggin above Bethel.

The entire valley of Crooked River has been carefully studied with regard to narrow places, sharp bends, and elevation of bed rock, and nothing has been found tending to disprove the belief that this was the course of a large river.

There are four passes between the headwaters of Crooked River and the Androscoggin, marked *F*, *G*, *H*, and *J* on Figure 5. The lowest pass (*F* on Fig. 5) is a mile north of the head of Songo Pond. Its summit elevation is 670 feet or only 35 feet above the Androscoggin. The pass is broad, flat, and swampy, and no ledge is visible in the pass or on its slopes; there is nothing to indicate bed rock near the surface, and therefore this pass is believed to be the drift-filled valley of the old river. Songo Pond is reported to be 40 feet deep, which places its bottom 25 feet below the Androscoggin and gives further evidence of a buried valley. The other passes are higher and will therefore not be considered further.

Profile 3 (Fig. 2) shows the grade of the Sebago River from Bethel to the sea. The full line represents the present surface, and where the old river course is now buried, its probable grade is shown by a broken line. A comparison of the profile of the Sebago River with that of the present Androscoggin (Profile 1) shows that the present river has a series of stretches with very

gentle gradient broken by falls, while the Sebago River has a constant grade without falls, indicating that the present course of the Androscoggin is partly at least of recent origin and that the course of the Sebago River was for a long time occupied by a large stream.

There is no obstacle today except glacial drift to prevent the Androscoggin from following its old course and a dam 40 feet high at Bethel would enable it to do so.

Sebago Lake is drained by the Presumpscot River, a short stream with seven falls and an indirect course. It is at once seen to be a postglacial stream without a rock valley, and it can be dismissed as a possible course for the Sebago River.

On the south side of Sebago Lake is Sebago Lake Station, where the Main Central Railroad crosses a very low divide. A rise of 20 feet in the lake would cause it to overflow here. The topography is typical of a terminal moraine; kames and kettles are numerous, and there are several kettle ponds.

This morainal dam marks the preglacial outlet of the Sebago Basin and the rock valley which the moraine now fills was undoubtedly the route of Sebago River.

Between Sebago Lake and the ocean the old valley is lost under a heavy mantle of till and extensive marine deposits. There are well-developed marine terraces at several levels near the coast.

The old valley probably reached the present shore in the vicinity of Old Orchard, where there is a broad indentation of the coast with no rock outcrops over a considerable area. Offshore soundings tend to confirm this view.

The valley of Sebago River from Bethel to the ocean has been located and described as fully as conditions permit. It presented, before being clogged with glacial drift, a natural course for a large river and is more probable as the preglacial course of the Androscoggin than the present route.

The Sebago River, which made this valley, had little in common with the present Androscoggin. One branch came from the Mount Winthrop Divide to Bethel, where it joined a branch from the valley of Sunday River.

South from Livermore Falls through Lewiston the present Androscoggin has a fairly direct north-south course in agreement

with the general trend of the topography. This region has not been studied in detail, but it appears probable that in preglacial times there was a river following a course similar to that of the present Androscoggin, between Livermore Falls and Lisbon Falls, and emptying into Casco Bay. This preglacial stream with the Little Androscoggin was the principal river between the Sebago and the Kennebec.

The Androscoggin River east of the mountains now occupies parts of two preglacial drainage systems. The main valleys of these two systems were clogged with drift in many places and the resulting drainage follows a circuitous route and empties into the Kennebec with a retrograde course.

CONCLUSIONS

This study has shown that the present course of the Androscoggin River is largely postglacial in origin.

It appears that in preglacial times there was a low divide at Mount Winthrop on the northeastward continuation of the main ranges of the White Mountains. All the drainage northwest of this divide went to the Connecticut River, passing through the valley now occupied by the Upper Ammonoosuc. This drainage system, including the Androscoggin above Dummer and the stream from Mount Winthrop Divide, is here called the "Mahoosuc" system.

Eastward from this old divide a stream flowed to Bethel where it was joined by a branch from the valley of Sunday River; and the stream resulting from their union, here called the "Sebago River," flowed southward through the valley now occupied by Crooked River, through the basin of Sebago Lake and into the ocean near Old Orchard.

East of the Sebago system was a north-south stream which with its tributaries, including the Little Androscoggin, drained nearly all the region between the Sebago and Kennebec rivers.

East of Bethel the drainage lines were greatly disarranged by heavy deposits of glacial drift. A single stream may occupy portions of several preglacial valleys and have other portions of its course of postglacial origin.

The capture of the Mahoosuc River by the Sebago River is probably not due to glacial disarrangement, but is best explained as preglacial piracy by the Sebago River.

The economic effects of these drainage changes are very important. The falls at Berlin and Gorham are due to piracy; and the pirate stream has not yet eroded the valley to grade. The falls at Rumford, Livermore, Lewiston, Lisbon, and Brunswick are due to the displacement of the river by glacial deposits. These falls furnish a large amount of valuable water power and there are important mills at all the places named. Prior to the rearrangement of the drainage there was probably little if any potential water power. When the pirate stream cut through the divide it made an easy route through the mountains which is now occupied by a railroad.

NOTES ON THE SAND DUNES OF NORTHWESTERN INDIANA

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Of the sand dunes of North America, few present more interesting phenomena than those bordering the southern shore of Lake Michigan. Not only do they illustrate all phases of dune activity but they have a significance in ecology and post-glacial history as well as rare scenic beauty. They are conspicuously developed in northwestern Indiana, their maximum development being confined to the 20 miles of shore between Gary and Michigan City. Heights of 100 feet are common and the height of the frontal ridge along the lake commonly ranges from 75 to 175 feet. Parts of the dune complex are fixed and forested, while in other areas the sand is being shifted. The dunes are limited largely to a belt about a mile wide along the shore, although in places low dunes extend several miles inland.

Along the western shore of Lake Michigan for 20 miles north of Chicago the waves are actively cutting into the thick drift, here composed of rather fine materials. This wave-cut cliff may be seen on the Highwood topographic map and in places is more than 80 feet high. A very considerable amount of erosion has taken place and some of the débris has been transported southward by the alongshore currents. Evidence of this movement is seen in the accumulations of sand on the northern sides of piers and the southerly deflection of streams entering the lake where unprotected by breakwaters. With the wear and sorting involved in the transportation, the material which reaches the southern end of the lake is almost exclusively quartz sand. Here the topography and prevailing winds are such that deposition takes place. The shore sands become the prey of the winds and the dunes reach their greatest development.

In order to examine the effect of the wind transportation on the sand grains, nearly fifty samples were gathered along seven lines

running back from the lake and at right angles to the trend of the shore. On the assumption that all of the dune sands had been blown inland from the present shore, it was anticipated that the sand would show increasing signs of wear with increasing distance from the shore. The microscope was used to determine the rounding of the grains, and for the gradations in size a tower of sieves was found most satisfactory. The customary procedure in the latter case was to weigh out 25 grams of sand and pass it through sieves of 60, 80, and 100 mesh to the inch, thus giving four grades of size, namely the sand retained in each screen and that passing through the 100 mesh sieve. These groups were then weighed and converted into percentages.

The percentage of coarse sand was found to decline back from the shore and there was a corresponding increase in the finer grades. At a distance varying from one-fourth to one-half mile from the beach, however, came a sharp increase in the proportion of coarse sand along most of the lines on which samples were taken. The change was quite regular, and reference to field notes showed that on the lakeward side of the location for each sample which showed the unexpected coarseness there was an area of muck or marsh. Subsequent field investigations showed a more or less continuous belt of this swamp or muck land between the dune belt nearest the lake and the next one to the south, the dunes to the south being lower and more rounded. Along the southern border of this flat there were in places topographic suggestions of an old beach ridge and from burrows of animals and holes which were dug, very coarse sand was found. In the analyses of the samples from the second dune belt, next south of the swamp belt, there was again a progressive decrease in size of grain grading to the south. The evidence, both topographic and petrographic, therefore points to an old shore line, the dunes immediately to the south having been built when the lake shore stood at its position, rather than having been blown inland from the present beach. The muck or marsh marks the approximate position of a former shore, and was perhaps developed behind a barrier beach.

The South Shore Electric Railway in the dune country runs parallel to the lake and about a mile south of it. Most of the dunes are north of the railroad but for much of the distance there

is a definite beach ridge, together with low dunes, just south of the road. Analyses of sand along section lines through this third belt of dunes showed an increase in the size of grain as compared with the sand immediately to the north, and on later search shells and pebbles were found. The evidence for a former strand line in this position is strong.

South of the third dune belt just referred to, especially in the neighborhood of Johnsville, there is another pronounced beach line banked with low dunes on the south. The beach here is well marked and strewn with beach-worn pebbles. None of these shore-line evidences were anticipated but were first suggested by variations in the coarseness of the sand. Since the interruption in the gradation of size was a rather regular phenomenon and scarcely to be accounted for if the sand had been subjected to greater wear, search was made for additional evidence of shore lines. In connection with each of the three suspected beach lines, additional criteria were found in the form of beach gravels or coarse sands, and in the case of the two beaches most distant from Lake Michigan the topographic evidence was strong.

The history of the dunes therefore appears to be closely associated with the development of Lake Michigan. With the northward retreat of the Late Wisconsin ice sheet a lake was formed in the Michigan basin, known as Lake Chicago. Since the present northern outlet was blocked by the ice, the water level was higher than now, the overflow being to the south through the Illinois River, as is well known. With the lowering of this channel and the uncovering of other outlets by the retreating ice front, there followed successive levels of the water. These halts are known as the Glenwood, Calumet, and Tolleston stages of Lake Chicago, the level of the water above Lake Michigan being respectively 56, 32, and 17 feet. In the absence of topographic maps or precise elevations in the area under consideration, determinations of the elevations of the old shore lines have not been made. Judging from the gradient of the two streams which cross the dunes and by the positions of the beaches in adjacent areas, it is thought best to assign the four belts of dunes to the various stages in the history of the lake, including the present. On this basis, each dune belt in the complex

dates back to a distinct period in post-glacial history, and while sand from one tract has been blown into the other belts, in places obscuring the evidence of a beach, each tract is on the whole distinct.

The exact locations of the shore lines have not been mapped in the region involved, and in some places this will be impossible because of the moving dunes; their approximate position, however, is as follows: Tolleston Beach passes through the southern border of Miller and along the southern margin of Long Lake. At Wicliffe it is doubtless north of the station on the electric line and beginning with the eastern border of the broad opening through the dunes at Wilson it is marked by the southern edge of the marsh or muck tract within the main body of the dunes; this continues almost to Michigan City. The Calumet Beach is just south of the Little Calumet River in Lake County, and as far west as Wilson where Lake Chicago had an extensive embayment. Beyond this it parallels the South Shore Electric Railway as far as Johnsville, being immediately south of it. The Glenwood Beach is south of the Michigan Central Railroad in the eastern portion of Porter County and after swinging south in a semicircle about the former embayment, strikes west south of Hobart, some seven miles from Lake Michigan.

Due to the complex processes which have shaped the sand it is difficult to make more than generalizations as to the rounding and polishing of the grains, and shifting winds render it impossible in some places to ascertain whether the sand at any given point has recently arrived or is part of the original material of the dune. Microscopic examination of the beach sand shows it dominantly subangular. It is generally rather transparent and little pitted, the corners frequently being sharp with little rounding. Back from the beach the characteristic description would be subspherical, many of the grains being well rounded and bean-shaped. All sand which has been subjected to sand-blast action is pitted and frosted, this being quite noticeable in the dune sand. Within the older dune belts this gradation from the former shore line landward is also apparent, but on account of the longer period of exposure and consequent aeolian wear of all the sand, the contrast between beach and dune sands is here less pronounced.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Berek, M. "Zur Messung der Doppelbrechung hauptsächlich mit Hilfe des Polarisationsmikroskops," *Centralbl. f. Min. Geol. u. Pal.*, 1913, 388–96, 427–35, 464–70, 580–82. Figs. 7.

The new Berek compensator here described is somewhat similar in pattern to the Nikitin quartz compensator. In the present case, however, the mineral plate is calcite. The author shows that the dispersion of mineral sections nearly at right angles to the optic axis becomes practically zero, consequently any inactive, uniaxial mineral is suitable. Since rather a thick section is required to give the higher orders of colors, quartz cannot be used on account of its rotary polarization. The construction of this instrument permits much more accurate measurements than that of Nikitin. A calcite plate, 0.1 mm. in thickness, cut at right angles to the optic axis, is attached to a rotatable axis in a slider which is to be inserted in the slot in the microscope above the objective. Since it is thus between the polarizing prisms, no cap nicol is required. The amount of rotation of the plate is read from a graduated drum and vernier to 2′. With the thickness of calcite used, it is possible to read colors to the fourth order. If higher readings are desired, the calcite plate may readily be removed and replaced by one that is thicker. The sensitiveness of this compensator is shown to be equal to that of Babinet for moderate double refraction, and greater for low colors.

Berek, M. "Über Zirkularpolarisation," *Fortschr. d. Min., Krist., u. Petr.*, IV (1914), 73–114, 221–62. Fig. 1.

A full discussion of the phenomenon of rotary polarization.

Berek, M. "Die astigmatischen Bildfehler der Polarisationsprismen," *Centralbl. f. Min. Geol. u. Pol.*, 1919, 218–24, 247–55, 275–84. Figs. 5.

The insertion of the nicol prism between the objective and ocular causes astigmatic and focal disturbances. The latter is usually com-

pensated by means of a lens above the analyzer, but the former has hitherto been left uncorrected. In this paper the cause of the astigmatism is discussed and lenses for its correction are suggested. Two photographs of the same slide show the remarkable improvement in definition with the corrected nicol.

BEREK, M. "Über die Berechnung der Polarisationsverhältnisse im Gesichtsfelde der Polarisationsprismen," *Verhandl. d. Deutschen Physikal. Gesell.*, XXI (1919), 338–46.

BEREK, M. "Die Schärfentiefe des Mikroskops," *Zeitschr. f. wissensch. Mikroskopie*, XXXVII (1920), 120–22. Fig. 1.

BEREK, M. "Uber die einfachen und zusammengesetzten charakteristischen Konstanten der Mikroskopobjektive," *Zeitschr. f. wissensch. Mikroskopie*, XXXVII (1920), 36–41. Figs. 2.

A discussion of the use of 250 mm. and Δ in the determination of the enlargement of objectives.

BERKEY, CHARLES P. "Geological Reconnoissance of Porto Rico," *Ann. N.Y. Acad. Sci.*, XXVI (1915), 1–70. Figs. 20, maps and profiles 2.

This is a report of the New York Academy of Sciences Expedition to Porto Rico undertaken, in part, to determine the nature and origin of the rock formation and to group them into series suitable for use in subsequent geological work. Two series are described—a younger, consisting of Tertiary shales, reef limestones, and recent deposits, and an older including tuffs, ashes, shales, conglomerates, limestones, and a great variety of probably pre-Tertiary intrusives. Igneous rocks described briefly are extrusive basalts and andesites, and intrusive andesite-prophyry, granite-porphyry, granite, and diorite.

BOEKE, H. E. "Die Eisenerze," *Die Umschau*, XXIII (1919), 289–92.

A popular article on the occurrence of iron ore.

BOWEN, N. L. "Differentiation by Deformation," *Proc. Nat. Acad. Sci.*, VI (1920), 159–62.

Discusses differentiation according to Darwin's theory of fractional crystallization and the squeezing out of the mother liquor.

BOWEN, N. L. "The Sodium-Potassium Nephelites," *Amer. Jour. Sci.*, XLIII (1917), 115–32. Figs. 2.

While this is strictly a mineralogical paper, it is of importance to petrographers in showing the inaccuracy of calculating nephelite as $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$. It is here shown that the molecules $NaAlSiO_4$ and $KALSiO_4$ are fundamental constituents of it, although they may be present in variable amounts.

BRAUNS, R. "Skapolithführende Auswürflinge aus dem Laacher Seegebiet," *Neues Jahrb.*, B.B., XXXIX (1914), 79–125. Pls. 2.

Describes seventeen different kinds of scapolite rocks from the Laacher Sea region. Numerous analyses are given.

BRAUNS, R. "Der Laacher Trachyt und seine Beziehung zu anderen Gesteinen des Laacher Seegebietes," *Neues Jahrb.*, B.B., XLI (1916), 420–502. Pls. 2.

This is a very complete study of the Laacher Sea trachyte and related rocks. Twenty-three new analyses are given, all of which are also recast into molecular proportions reduced to 100, and computed according to Osann's system. Nine older analyses are quoted for comparison. A history of volcanic activity in this region is given, and the following conclusions as to the relationships of the rocks are reached: The white pumice, the Dachsbusch trachyte, and the light Laacher trachyte are so closely related chemically that they are thought to have been derived from the same magma, their differences in habit being due to the action of the inclosed gases. Petrographically they may be designated phonolitic trachytes and trachytic phonolites. Further, these rocks are closely related chemically to the adjacent noselite-phonolites, and it is probable that they came from the same magma, their differences being due perhaps to greater differentiation or to assimilation of crystalline schists. The dark Laacher trachyte is more

closely related to the tephrites of the region, and it is assumed that the trachyte assimilated some of its constituents. The oldest and at the same time most basic rocks of the region are the tephritic lavas. These are followed by younger and progressively more acid noselite-phonolite, white pumice, and finally light trachyte. Among the ejectamenta are fragments having the character of dike rocks, some of which are more basic than the tephrites, and others more acid than the Dachsbusch trachyte. Fragments of plutonic rocks, so far as these have been analyzed, show intermediate chemical characters. The rocks are all fully described and only lack estimates of the mineral percentages to present good word-pictures of their appearance.

BRAUNS, R. "Neue skapolithführende Auswürflinge aus dem Laacher Seegebiet," *Neues Jahrb.*, I (1917), 9–44. Pls. 2.

Nine more scapolite-bearing rocks from the Laacher Sea region are described. There are many analyses, and a determination of the refractive index of the sulphate scapolite.

BRAUNS, R. "Über aufgewachsene Karlsbader Zwillinge von Sanidin vom Laacher See," *Neues Jahrb.*, I (1917), 45–49. Pl. 1.

BRAUNS, R. "Einige bemerkenswerte Auswürflinge und Einschlüsse aus dem niederrheinischen Vulkangebiet," *Centralbl. Min. Geol. u. Pal.*, 1919, 1–14. Fig. 1.

BRENNER, TH. "Über Theralit und Ijolit von Umptek auf der Halbinsel Kola," *Bull. Com. Géol. Finlande, No. 52*, 1920, 1–30. Figs. 4.

Here are described the Kola Peninsula theralite, and a new ijolite from the Tachtarwun Valley. The descriptions are elaborate and good with the exception of the omission of an estimate of the mineral percentages in the theralite. Omissions of this kind lead to such errors as the statement that "es giebt sowohl grobkörnige, helle als kleinkörnige, dunkle Arten." But theralite is a name given by Rosenbusch to certain nephelite, plagioclase plutonic rocks which he thought were represented by certain tephrites and basanites described by Wolff from the

Crazy Mountains. As a matter of fact, they were first found some years later by Wolff in Costa Rica. While in his first published description Rosenbusch does not make the predominance of the dark constituent a necessary qualification, in his later works he grouped the theralites and shonkinites, and said of them: "Die Theralithe und Shonkinite sind hypidiomorphkörnige Tiefengesteine, welche *bei starker Vorherrschaft der dunklen Gemengtheile* durch die Mineralcombination Nephelin mit Kalknatronfeldspath, bezw. Nephelin mit Kalifeldspath, charakterisirt sind," consequently there can be no light theralites. The analyses of various theralites are recast into both the C.I.P.W. and Osann's system. The ijolite is described fully and analyzed. It differs from the usual ijolites in the presence of arfvedsonite-hornblende. The modal percentages determined by the Rosiwal method are: nephelite 38.25 per cent, arfvedsonite-hornblende 31.96 per cent, aegirite-augite 16.24 per cent, titanite 5.78 per cent, mosandrite 3.81 per cent, magnetite 2.37 per cent, apatite 1.59 per cent. The rock, consequently, may be classified as 3126 (new form, or 3131 old form) of the reviewer's system. The chemical analysis of the rock is computed in the C.I.P.W. system as Ivaaros, and is compared with three other ijolites, one a Malignos, one an Ivaaros, and one an Ijolos. In an appendix are given analyses of fifty-four theralites and related rocks.

REVIEWS

The Geology of Hardin County and the Adjoining Part of Pope County. By STUART WELLER with the collaboration of CHARLES BUTTS, L. W. CURRIER, and R. D. SALISBURY. Illinois Geological Survey, Bull. No. 41, 1920. Pp. 377, pls. 11, figs. 27.

This report represents the results of three seasons' field work by the author in conjunction with Messrs. Butts and Lee of the U.S. Geological Survey and part of two seasons by Mr. Currier in the study of the fluorspar deposits of the county. In addition a chapter on the geography of the region is contributed by Mr. Salisbury.

Hardin County lies in the southeastern part of the state and wholly within the Ozark country, an area of considerable relief and in a mature stage of dissection. The history of the topography involves four periods of uplift, the three cycles of erosion other than the present one, being known as the Karber's Ridge, McFarlan, and Elizabethtown cycles.

Structurally the area is characterized by rather flat-lying strata surrounding an area of doming and intense faulting. The faults are of the normal type and form a network along the edges of the dome which is roughly circular in outline. They originated through the collapse of the dome. Likewise remarkable is the presence within the region of igneous intrusives in the form of dikes, sills, and plugs. The origin of the dome involves the intrusion of these rocks, the collapse following either the gradual spreading out of the lava or its partial withdrawal. The structure is remarkable and has but few known parallels.

The rock formations of the region include Devonian, Mississippian, and Pennsylvanian sediments, involving a thickness of some 4,000 feet. Of special note is the contribution to the knowledge of the Chester group.

The oldest formation present, known locally as the Devonian limestone, is correlated with the Lower Devonian, Onondaga, and Hamilton. Lithologically it is a unit. The overlying Chattanooga shale contains but a meager fauna and from its stratigraphic relation may be correlated with either the Upper Devonian or Lower Mississippian, or both.

The Meramec group, as originally defined by Ulrich, included the Warsaw, Spergen, and St. Louis limestones. A study of the Ste. Genevieve faunas convinces Professor Weller that this formation is much

more closely related to the St. Louis group than to the Chester with which Ulrich had allied it, chiefly due to the presence of a species of the typical Chester genus *Coeloconus*. On this basis and the recent recognition of an unconformity separating the Renault and Ste. Genevieve formations, Weller redefines the Meramec group so as to include the Ste. Genevieve.

This report represents the most recent work on the subdivision of the Chester and the correlation of these units. Especial attention is called to the following corrections of previous correlations of the formations of southeastern Illinois and Kentucky with those of Randolph County: (1) the Renault and Shelterville formations, the Upper Ohara of Ulrich, are correlated with the Renault. Professor Weller considers those species of the genus *Talarocrinus* with the thickened plates forming bilobed basis as very characteristic of the Lower Chester. This fauna is typically developed in the Upper Ohara; (2) the Golconda limestone with the Lower Okaw; (3) the Cypress sandstone with the Ruma; and (4) the Bethel sandstone with the Yankeetown formation. Methods of correlation are discussed in detail.

The igneous rocks of the region are found chiefly in the vicinity of the Ohio River where the more rapid erosion has exposed them. They are of three types: fine-grained, dark-colored lamprophyres, medium-grained, dark-colored peridotites, and volcanic breccia.

Economically Hardin County is noted for its fluorite deposits, the annual output of the county being over two-thirds that of the country. Fluorite occurs as (1) vein deposits, replacing calcite fillings of the fault planes; (2) bedded deposits where fluorite has replaced limestone bedrock; and (3) superficial residual deposits. Small quantities of lead and zinc are recovered incidental to the fluorspar exploitation. The origin of the deposits involves (1) doming and faulting in post-Pennsylvanian, (2) deposition of calcite in the fault fissures, (3) mineralization by fluriferous magmatic solutions replacing calcite, and (4) the introduction of metallic sulphides.

The only other large resource of the region is agriculture. There is an abundance of limestone suitable for lime, cement, and ground rock for fertilizer, as well as an unlimited supply for road metal. In regard to the oil and gas possibilities, while the structure is favorable, but little is known of the underlying pre-Devonian sediments.

In the portion of the bulletin devoted to systematic paleontology, the work is limited to those common species in need of further illustration and description and to those forms important for their bearing upon

the correlation problems. The majority of these are Chester forms, together with some Ste. Genevieve and St. Louis species. Of interest is a new species of *Septopora*, *S. similis* from the lower St. Louis which is almost identical in character with the Chester *S. subquadrans*. This occurrence is noteworthy in that the genus *Septopora* has hitherto been considered highly characteristic of the Chester. Seventy-two species are described and figured, prominent among which are species of *Talarocrinus* and *Pentremites*.

A. C. McF.

On the Crinoid Genus Scyphocrinus and Its Bulbous Root Camarocrinus. By FRANK SPRINGER. Memoir Smithsonian Institution, 1917. Pp. 74, pls. 9, figs. 16.

For more than a half-century there have been known to paleontologists certain bulb-like, supposedly crinoidal or cystoidal, bodies which were described from American localities in 1869 by Hall as *Camarocrinus*. Similar structures had been known for some time from the Silurian of Bohemia where they had been found by Barrande. He had named them *Lobolithus* without describing them.

In 1904 Schuschert summarized all the known facts touching the occurrence and relations of this form. He found that these structures were of widespread occurrence in both Bohemia and America. In the former they were confined to a horizon equivalent to the American Rochester shale, and in the latter to the Manlius and Helderbergian. In Bohemia they were commonly associated with the genus *Scyphocrinus* which was as yet undescribed from America. They were frequently found in beds void of any other crinoidal remains and a large majority were found in strata with their stalked end down. He came to the conclusion that

> *Camarocrinus* thus appears to be the float of an unknown crinoid, that was held together after the death of the individual by the firmly interlocked double walls of the exterior and interior, while the crown and stalk dropped away. Under this hypothesis the float drifted with the sea currents, was finally filled with water and, the attenuated end being heavier, sank in that position.

It is the purpose of this paper to present the results of some later studies by Mr. Springer which have resulted in a change in the conception as to the functional nature of the so-called *Camarocrinus*. He finds not only that the genus *Scyphocrinus* does occur in abundance in America but that the *Camarocrinus* bulbs are directly connected at the distal end of the stem of crinoids belonging to that genus. Moreover

these bulbs, when in their original position, occur with the stalked end upward and not downward as previously supposed, the bulb being merely a distal specialization of a true root and not a float.

The bulb-like process may itself be described as a

> rigid, hollow, chambered root, consisting of a large spheroidal bulb with a short projecting collar, a stem base with bifurcating roots resting in and forming a large part of the floor within the collar; and several internal, laterally opposed sacs which abut against the inner side of the bulb wall. . . . . The collar and bulb wall consist of single layers of similar plates derived from rootlet systems originating at the ends of the proximal root branches.

Eight species of *Scyphocrinus* occurring in America are described and are figured together with several species of other genera. A table of analysis of the American forms is given.

A. C. McF.

The American Species of Orthophragmina and Lepidocyclina. By JOSEPH A. CUSHMAN. Shorter Contributions to General Geology. U.S. Geological Survey, Professional Paper 125 D, 1920. Pp. 39–108, pls. 7–35.

The genera *Orthophragmina* and *Lepidocyclina* belong to the group of orbitoid *Foraminifera*, a group of excellent horizon-markers due to their limited stratigraphic range, wide geographic distribution, and great abundance in the Tertiary. Hitherto the group has received but little attention by American paleontologists. In the present paper the author describes all known American species, which form but a small percentage of those which he believes will be later described and have been described from the European Tertiary.

Orthophragmina includes those species characterized by the presence of rectangular chambers in the equatorial band. The genus is limited, so far as known, to the Eocene, and in America, chiefly to the upper part. *Lepidocyclina* differs in that the chambers of the equatorial belt are typically hexagonal. It ranges through the Eocene, and Lower and Middle Oligocene.

Sixteen species of *Orthophragmina* are described, of which two are new, and thirty species and varieties of *Lepidocyclina* of which eleven are new. The author includes a table of tentative correlations of the Tertiary of Panama by T. W. Vaughan, a key to the species of *Lepidocyclina* and a list of those species which are considered as good index forms for the Tertiary of the Coastal Plain.

A. C. McF.

North American Early Tertiary Bryozoa. By FERDINAND CANU and RAY S. BASSLER. United States National Museum, Bull. No. 106, 1920. Pp. 878, pls. 162, figs. 279.

This monograph forms a pioneer work in the field of American bryozoölogy. Despite the great abundance and splendid preservation of bryozoa along the Atlantic and Gulf Coast regions, there has hitherto been so little done with them as to leave the field almost virgin.

Under the term Lower Tertiary the authors have included the Midwayan, Wilcoxian, Claibornian, Jacksonian, and Vicksburgian formations. There is found here a much richer bryozoan fauna than in the succeeding formations. A study of the Miocene, Pliocene, and Pleistocene bryozoans has been completed and it is hoped that it will soon appear as a monograph supplementing the present work. An extensive table showing the geographic and stratigraphic distribution of the different species is given.

Tertiary bryozoans are so intimately related to living forms that a thorough knowledge of the taxonomy and anatomy of living species is necessary for the proper classification and interpretation of the structures found. Accordingly the authors have produced a monograph which is of use both to the zoölogist and to the paleontologist. Numerous text figures are introduced to make the report of value to the non-specialist. A detailed discussion of the structure and classification of living forms is given.

With the exception of one undetermined species, referred to the order *Ctenostomata*, all Tertiary bryozoans belong either to the *Cheilostomata* or *Cyclostomata*, the latter being about half as numerous as the former. These are included in the subclass *Gymnolaemata*, which includes all fossil bryozoans, and is characterized by a circular row of tentacles surrounding the mouth. It is in turn incorporated in the class *Ectoprocta* which is distinguished by the presence of the anal orifice outside the row of tentacles.

The *Cheilostomata* which were probably derived through the Paleozoic *Trepostomata*, differ from the *Cyclostomata* in that they may be either calcareous or chitonous, and the aperture is closed, upon the retraction of the polypide, by an operculum. The *Ctenostomata* are chitonous or gelatinous forms with the aperture closed by a tooth-like process.

The studies of the authors have led them to discard for the present the former major classification of the *Cyclostomata*, retaining for convenience only the two larger divisions the *Ovicellata* and *Inovicellata*. In classifying the *Cheilostomata* orders were based upon general mor-

phology, suborders on the form of aperture and operculum, and families on the presence of cardelles, lyrula, ovicells, and radicells.

With the increased recognition of the value of bryozoans as horizon-markers, the student will find this systematic report a reference of constant value.

A. C. McF.

Louisiana Lignite. By ROBERT GLENK. Department of Conservation, Division of Economic Geology, State of Louisiana, Bull. No. 8. New Orleans, 1921.

Although Louisiana lignite has been consistently mapped on all fuel maps of late years as a possible source of low-grade fuels, it has not until recently begun to receive the attention that it merits. The report here reviewed shows a gratifying interest by the state of Louisiana in its available resources—an interest that, since the days of Harris' and Veatch's work on the state survey, appeared to have flagged.

The lignite of Louisiana is of Eocene age and distributed vertically in the Wilcox, Claiborne, and Jackson groups. It varies in thickness from a few inches to twenty feet. Interesting paleobotanical collections have been made from it. In the adjacent states of Texas and Arkansas lignite is mined in considerable quantities by stripping the overburden, or by the room-and-pillar method where the dip of the lignite bed is appreciable; similar methods, though not yet used in Louisiana, might well be applied there in the future.

Figures expressing the lignite reserves of the state are not presented; they would be interesting and useful. Analyses of several Louisiana lignites yielded the following:

	Percentage
Moisture	5–47
Volatile combustible matter	30–75
Fixed carbon	5–40

The highest thermal value obtained was 8,046 B.T.U.'s. The analyses presented show Louisiana lignite to be of an intermediate grade. With destructive distillation the end products were:

	Percentage
Aqua ammonia	20 –30
Tar	4.5– 5
Carbonized residue	50 –56
Gas and loss	18 –20

The carbonized residue has a heating value equal to good anthracite; an average ton of lignite yields 8,000 cubic feet of gas (mainly hydrogen,

methane, and carbon monoxide) with a heating value of 450 B.T.U.'s per cubic foot; this is a higher value than producer gas or Mond gas, but lower than coal gas or natural gas.

In general it appears that the chief use to which Louisiana (and probably all Gulf Coast) lignite can be put is in the briquetting of the carbonized lignite, with the recovery of the tar and ammonia as by-products and the utilization of the gas in producing electric power. Such a use avoids the difficulties involved in shipping and storing the combustible fuel, and makes available to the Gulf States, where hydraulic power is not always obtainable, a cheap source of electricity.

The report, although in a large measure a compendium of other works on the subject, presents a series of original and very careful fuel analyses, and is a most valuable addition to the scanty information on the subject of the geology and technology of utilizing Louisiana lignites.

C. H. B., Jr.

A Glossary of the Mining and Mineral Industry. By Albert H. Fay. U.S. Bureau of Mines, Bulletin 95. Pg. 754. Washington, 1920.

This glossary constitutes a noteworthy contribution to mining literature. It contains about 20,000 terms; these include both technical and purely local terms, relating to metal-mining and coal-mining, quarrying, and the recovery of petroleum and natural gas, as well as many metallurgical terms. It includes also the names of useful and important common minerals and rocks, and geological terms. The glossary presents, in a single comprehensive volume, essentially all of the terms in use in the mineral industries in English-speaking countries, together with most of the Spanish terms in use in the United States and in Latin America. In addition it includes terms relating to ceramics and glass-making, foundry practice, railway and building construction, electrical installation and power-plant equipment, and chemical terms relating to metallurgical practice.

E. S. B.

Geology of the Yellow Pine Cinnabar District, Idaho. By E. S. Larson and E. C. Livingston. U.S. Geological Survey, Bulletin 715 E. Pp. 12. Washington, 1920.

The Yellow Pine cinnabar district, in Valley County, Idaho, is about 70 miles from the town of Cascade. The cinnabar ore bodies appear to be in irregular lenses or chimneys of silicification in limestones which have been intruded by dikes and irregular bodies of rhyolite

porphyry, and the cinnabar, which is the chief sulphide in the ore, lies in part in chalcedonic silica, and in part in friable marble adjoining such silica. Some pyrite is present with the cinnabar in most of the deposits. Stibnite is present in the district, in association with cinnabar, but was not observed in any of the workable deposits.

Cinnabar was discovered in this district in 1902, and prospecting has been active since that time. In 1917 active development on a small scale was in progress. E. S. B.

Coal in 1918. Part A: Production. By C. E. LESHER. "Mineral Resources of the United States, 1918," Part II. Washington: U.S. Geological Survey. 118 pp. 1920.

A noteworthy feature of this report, as contrasted with reports for preceding years, is the detailed statistical study, by states and for the United States, of the causes of loss of time in the coal-mining industry. In a series of instructive diagrams for the United States and for each state, the percentage of time lost on account of (*a*) car shortage, (*b*) labor shortage and strikes, (*c*) mine disability, (*d*) lack of market are separately shown. These statistical studies are timely because they throw light upon the causes of the industrial troubles which have vexed the coal industry in recent years. E. S. B.

Some Principles Governing the Production of Oil Wells. By CARL H. BEAL and J. O. LEWIS. Bureau of Mines, Bull. No. 194, Petroleum Technology 61, 1921.

We are constantly reminded that the resources of petroleum in the United States are diminishing at an alarming rate. The fact that more oil was produced in the United States during the month of March, 1921, than during any previous month suggests that efforts to curtail production are futile. One of the best remedies for this situation is to make the most of what we have. In this we have been very successful through the Bureau of Mines.

Mr. Carl H. Beal and Mr. J. O. Lewis, the authors of this new publication, were among the first to make intensive studies of underground conditions in oil fields, so that the maximum production might be obtained from oil wells. The results have been gratifying and have more than paid for the cost of investigations.

The bulletin is a summary of all the known factors controlling the production of oil, and contains some of the theoretical aspects of oil production. It is of inestimable value to operators and "resident geologists." W. O. G.